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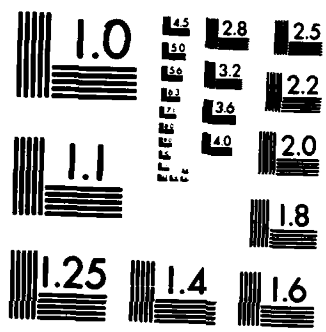

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Human Assembly Time Versus Levels of Visual and Tactile Sensory Input: Experimental Results for Five Devices

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CMU-RI-TR-84-22

The Robotics Institute
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September 1984

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Results are reported of laboratory experiments where levels of visual and tactile sensory input of human subjects are controlled and time required to assemble several types of devices is measured. There is an inverse relationship between the time to assemble a device and the amount of sensory input available to the subject. The results indicate that different types of assembly tasks require different types and amounts of sensory information processing. Another result is that the impact of a change in the level of tactile sensory input on assembly time depends on the available level of visual sensory input, and the nature of the interaction between

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visual and tactile information varies across the different assembly tasks. An analysis of the extent to which elemental manipulative subtasks (as categorized by the Methods Time Measurement System) are affected by changes in the level of visual and tactile sensory information is presented. Results are also reported of experiments where the levels of visual input and manipulative capability of human subjects are controlled.

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Abstract

Results are reported of laboratory experiments where levels of visual and tactile sensory input of human subjects are controlled and time required to assemble several types of devices is measured. There is an inverse relationship between the time to assemble a device and the amount of sensory input available to the subject. The results indicate that different types of assembly tasks require different types and amounts of sensory information processing. Another result is that the impact of a change in the level of tactile sensory input on assembly time depends on the available level of visual sensory input, and the nature of the interaction between visual and tactile information varies across the different assembly tasks. An analysis of the the extent to which elemental manipulative subtasks (as categorized by the Methods Time Measurement System) are affected by changes in the level of visual and tactile sensory information is presented. Results are also reported of experiments where the levels of visual input and manipulative capability of human subjects are controlled.

Additional keywords: experimental design.

1. Average Assembly Time Versus the Degree of Capability

1.1 Overview

This paper reports the results of a series of laboratory experiments where we control the levels of visual and tactile sensory input of human subjects and measure the time required to assemble several types of devices. We also report the results of assembly experiments where we control the levels of visual input and manipulative capability of human subjects. The motivation for performing these experiments is explained in a companion paper, *The Sensory Feedback Dependence of Assembly Tasks as a Measure of Comparative Advantage of Human Workers vis-a-vis Sensor-Based Robots*, by Robert U. Ayres (1984).[1]

The results show that there is an inverse relationship between the time to assemble a device and the amount of sensory input available to the subject. The time required to assemble a device increases as the amount of visual and tactile information is restricted.[2] For each device assembled, we measure the percentage change in assembly time when subjects shift from one level of visual and tactile input to another. These percentage changes show the degradation in time that results from restricting the level of sensory input. Restricting the levels of visual and tactile input to human subjects affects assembly times of different devices to different degrees. A given restriction in the level of visual or tactile input results in a significant increase in assembly time with some devices, but not with other. The results indicate that different types of assembly tasks require different types and amounts of sensory information processing. Another result is that the impact of a change in the level of tactile sensory input on assembly time depends on the available level of visual sensory input, and the nature of the interaction between visual and tactile information varies across the different assembly experiments. In the second set of experiments, manipulative capabilities are restricted and subjects assemble devices with two hands, one hands and two fingers, varying the level of visual input. In these experiments, the time to assemble a device also decreases as the levels of visual input and manipulative capability are restricted.

This report proceeds as follows. The results of assembling the various devices under the varying levels of sensory information and manipulative capability are discussed in Chapter 1. A description of the the experimental design is given in section 1.2. The discussion of the experimental results for

[1] Available as a technical report from the Robotics Institute, Carnegie-Mellon University.

[2] There are a few exceptions to this general rule, almost all of which are due to random variation in the experimental results.

assembling the devices under two levels of sight (full sight and no sight) and four levels of taction is given in section 1.3.1. Next, the results for assembling the devices under four levels of vision and four levels of taction are discussed in section 1.3.2. This builds on the discussion in section 1.3.1, and adds the additional results for the two intermediate levels of vision. The results for assembling the devices under two levels of sight (full sight and no sight) and three levels of dexterity (2 hands, 1 hand and 2 fingers) are discussed in section 1.4. All tables and figures reporting times to assemble the five devices and percent changes in times when shifting from one condition to another are given in section 1.5.

In chapter 2, an analysis of the the extent to which elemental manipulative subtasks are affected by changes in the level of visual and tactile sensory information is presented. The Methods Time Measurement (MTM) System is used as the basis for categorizing the elemental manipulative subtasks which comprise the assembly of a typical device. For each MTM subtasks, we estimate how its completion time is affected by a restriction in the amount of visual and tactile information. This information is summarized in the tables following section 2.2.

1.2 Experimental Design

1.2.1 Conditions Tested

The two types of variables controlled in these experiments are the capabilities of human subjects and the devices assembled. The human capabilities that are controlled, and the combinations of capabilities that are tested are shown in Table 1-1. In the first set of experiments, subjects assemble each device with their thumb and forefinger, while the input of information transmitted through the eyes and hands is systematically controlled. The input of visual information is controlled by having subjects look through different materials which vary in the degree to which they obstruct normal vision. Vision is controlled at four levels:

- sight unimpeded (full vision)
- sight partially impeded by looking through a gauze bandage
- sight partially impeded by looking through a sheet of wax paper
- sight fully impeded by blindfolds

In the first case, subjects performed the assembly experiments with their vision unimpaired. In the second case, subjects looked through a Johnson and Johnson brand *Steri-Pad* sterile pad that was attached to a pair of plastic safety glasses. In the third case, subjects looked through a sheet of Scott

Table 1-1: Human Capabilities Controlled and Combinations of Capabilities Tested

Capabilities Examined	Levels of Control
Vision	Full sight (FS)
	Gauze bandage blinders (GB)
	Wax paper blinders (WB)
	No Sight (NS)
Taction	No gloves (NG)
	Lightweight rubber gloves (LG)
	Heavyweight rubber gloves (HG)
	Wooden splint gloves (WG)
Dexterity	2 hands (2H)
	1 hand (1H)
	2 fingers (2F)

Combinations of Capabilities Tested

Varying Levels of Vision and Taction

Level of Dexterity: Fixed at 2 fingers
16 conditions
5 subjects
5 replications per subject per condition

Varying Levels of Vision and Dexterity

Level of Taction: Fixed at No Gloves (Bare Hands)
6 conditions (Sight/No Sight x 3 Levels of Dexterity)
5 subjects
5 replications per subject per condition

brand *Cut-Rite* wax paper attached to a pair of plastic safety glasses. In the fourth case, subjects were blindfolded. No attempt was made to formally quantify the amount of visual information transmitted to a subject under each of the four levels of vision tested. We assume that the amount of visual information transmitted to the subject decreases as we shift from unimpeded (full) sight, to looking through gaze bandages, to looking through wax paper, to being blindfolded.

Tactile information, in our context, refers to all information acquired by physically touching an object with the hand.[3] The input of tactile information is controlled by having subjects cover their hand with materials of varying degrees of thickness.[4] Taction is controlled at four levels

1. bare hand (full taction)
2. hand covered by lightweight rubber dishwashing gloves
3. hand covered by heavyweight rubber work gloves
4. two fingers covered by wooden splints

In the first case, the thumb and forefinger of the subject are not covered, and the other three fingers of the hand are taped together to prevent them from being used (Figure 1-1). In the second case, the hand is covered with a lightweight rubber dishwashing glove purchased from a supermarket, and the three fingers not used are taped together (Figure 1-2). In the third case, the hand is covered with heavier weight rubber glove purchased from a hardware store and three fingers not used are taped together (Figure 1-3). In the fourth case, a segment of a wooden splint (a tongue depressor from a doctor's office) is taped against the inside of the thumb and forefinger, and the three fingers not used are taped together (Figure 1-4). No attempt was made to formally quantify the amount of tactile information transmitted to a subject under each of the four levels of taction tested. We assume that the amount of tactile information transmitted to the subject decreases as we shift from a bare hand (full taction), to the hand covered by a lightweight rubber glove, to the hand covered by a heavyweight rubber glove, to the thumb and forefinger covered by a wooden splint.

In the second set of experiments, subjects assemble each device with their bare hands (full taction), while the input of visual information and the number of fingers used is systematically controlled. Visual information is controlled at two levels: full sight and no sight. The number of fingers used for assembly is controlled at three levels:

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[3] Overviews of tactile sensing, with emphasis on requirements for robots, are given in the following references. Harmon, Leon D., *Touch-Sensing Technology: A Review*. Technical Report MSR80-03, Society of Manufacturing Engineers, 1980. Coiffet, Philippe, *Robot Technology. Volume 2: Interaction with the Environment*. Prentice-Hall, Inc., 1983, chapter 4.

[4] Since subjects are only using two fingers of one hand to assemble, only one hand needs to be covered.

1. ten (two hands)

2. five (one hand)

3. two (two fingers)

In the text, we refer to these three conditions, two hands, one hand, and two fingers, as levels of dexterity.

The five assembly tasks are as follows:

1. To assemble a pencil sharpener

2. To screw a nut onto a bolt

3. To assemble a flashlight

4. To assemble tinker toy components

5. To insert wires and chips (dual-inline packages) into specific holes in a circuit board.

Diagrams of these devices are shown in Figures 1-5 through 1-9.

1.2.2 Experimental Design

Five subjects were used to assemble each device under the 16 conditions in the first set of experiments and the 6 conditions in the second set.[5] Each subject repeated each experiment five times. The order in which each subject performed each experiment was randomized in order to randomize the affects of cumulative learning as a result of repetition. The number of subjects used and the number of repetitions performed per experiment were limited to these small numbers because of time constraints.[6] In the first set of experiments, where vision and taction are controlled, the same five subjects are used to perform the time trials for each of the five devices. When vision and dexterity are controlled, the five subjects used to perform the time trials for each of the assembly tasks are not the same.

Task performance times were measured by an observer with a stopwatch. All time trials were videotaped. Average assembly times for the first set of experiments (vision x taction) are shown in

[5] In the first set of experiments (vision and taction), the five subjects are used to assemble each device were the same people. In the second set (dexterity and taction), they were not.

[6] For two devices in the second set of experiments, 13 replications were carried out in order to examine the effects of more replications on assembly time. The median times with 5 replications were 10 to 30 percent higher than with 13 replications. Thus, if each experiment were repeated more times, it is likely that average times would be lower. We are more interested in the relative change in time across conditions than in the absolute times. It was assumed that the effects of "learning-by-doing" would cancel out, assuming improvements in performance resulting from repetition affected each of the conditions equally.

Figure 1-1: Level of Taction: No Glove (Bare Hand)

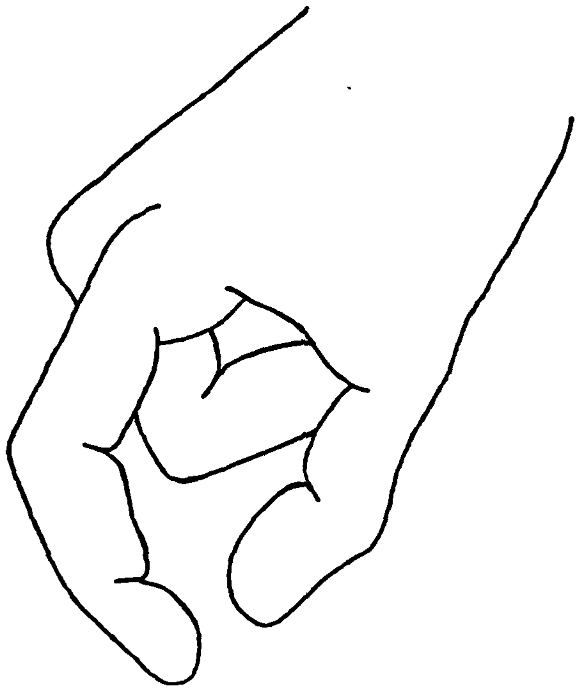
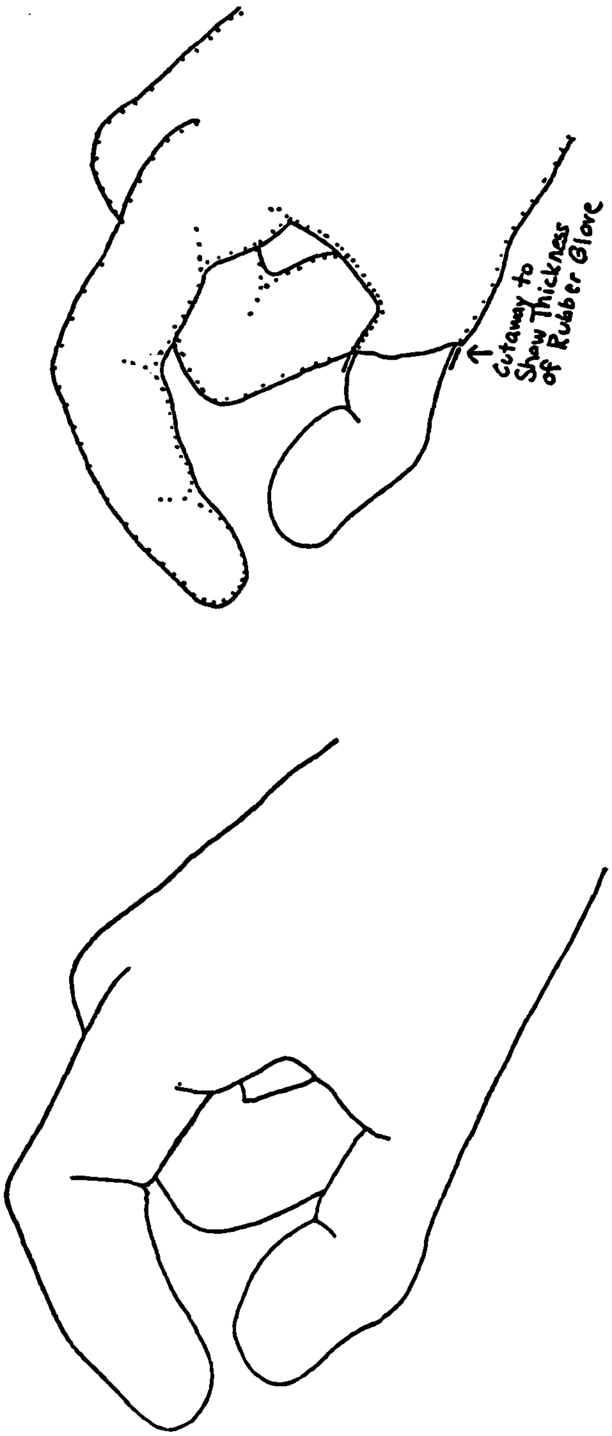
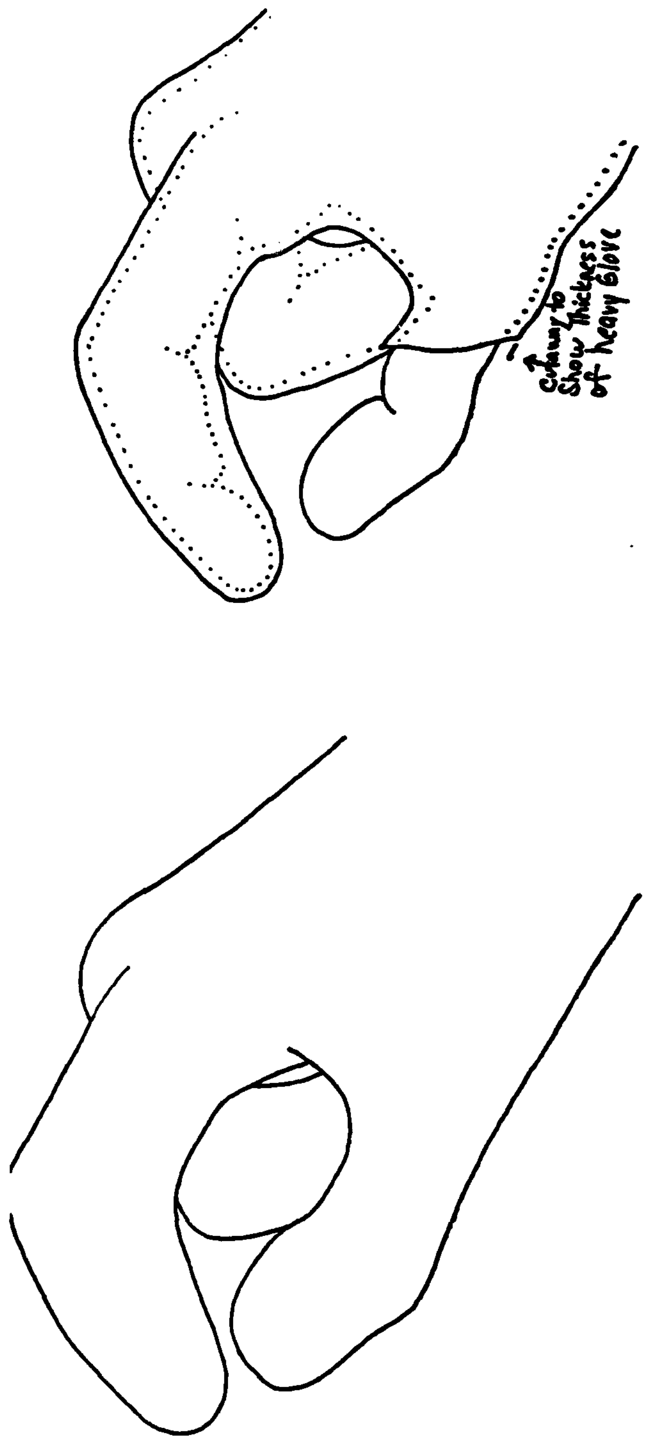


Figure 1-2: Level of Taction: Lightweight Rubber Glove



Glove thickness: .0013"

Figure 1-3: Level of Taction: Heavyweight Rubber Glove



Glove thickness: .060"

Figure 1-4: Level of Taction: Wooden Splint Glove

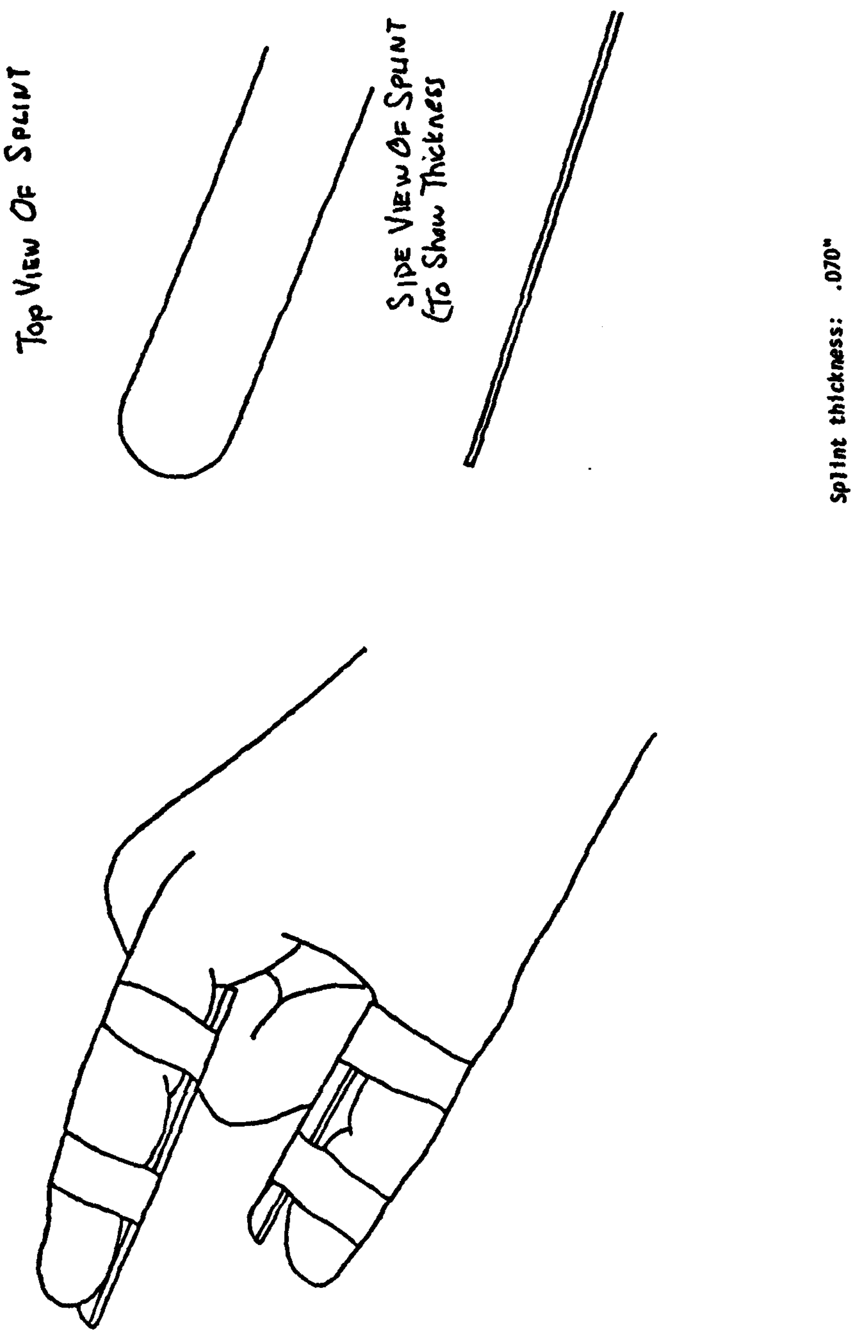


Figure 1-5: Components of Pencil Sharpener Assembly Task

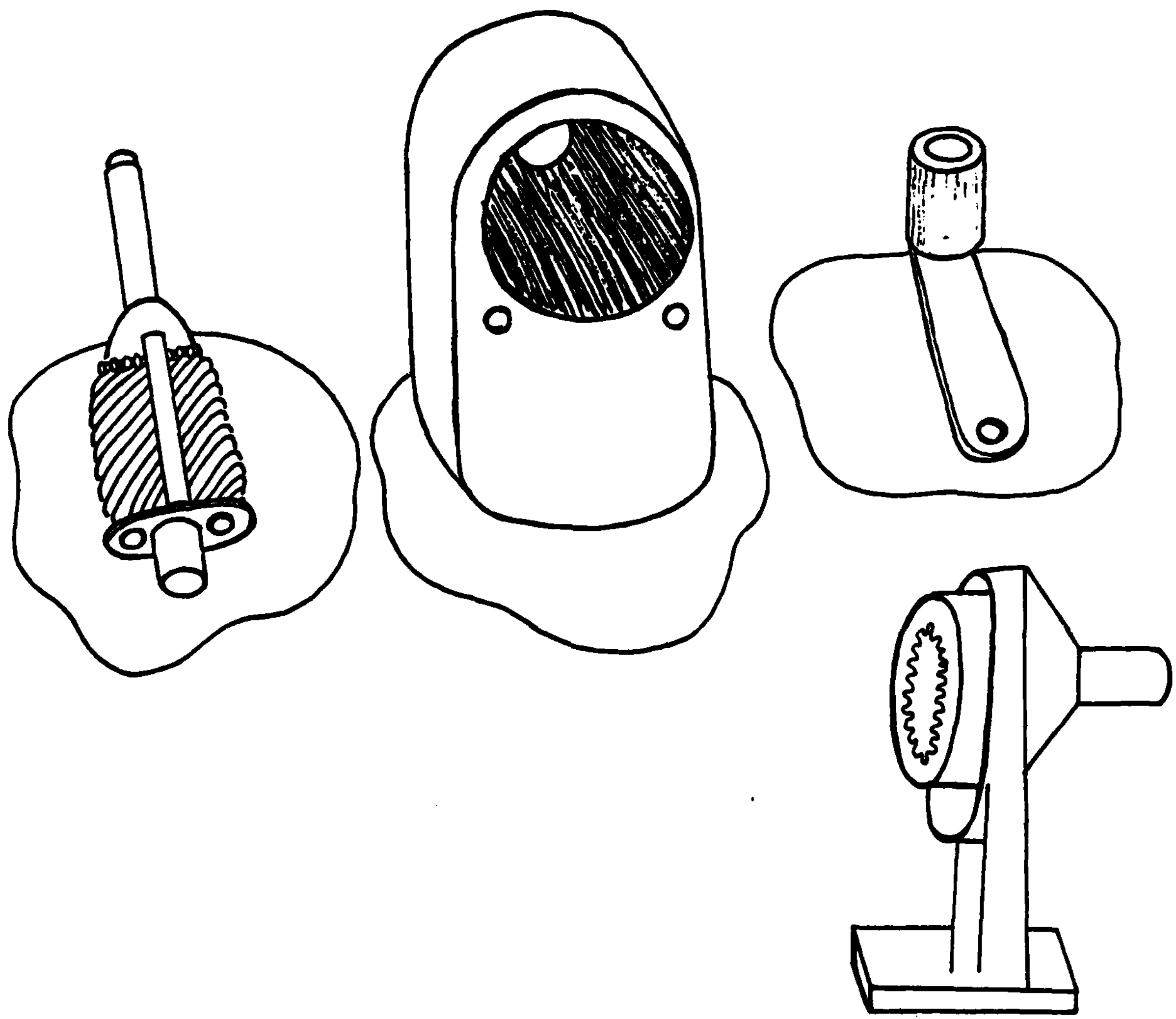


Figure 1-6: Components of Nut and Bolt Assembly Task

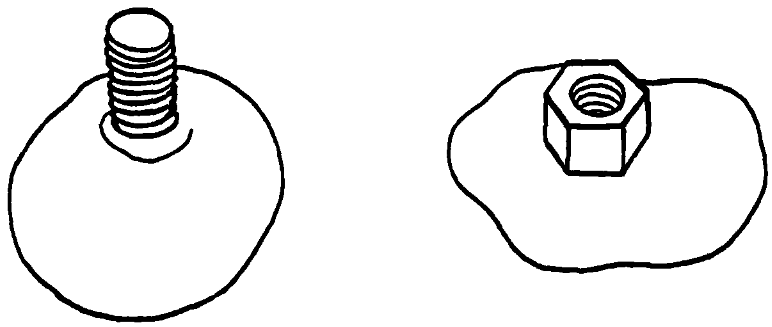


Figure 1-7: Components of Flashlight Assembly Task

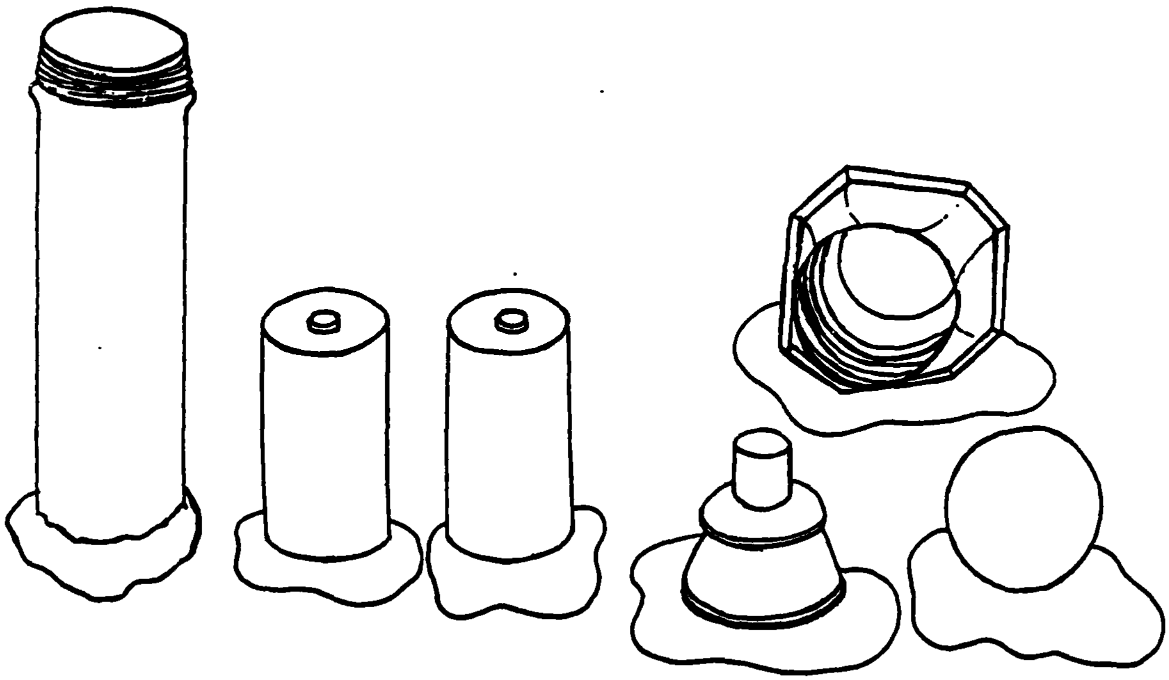


Figure 1-8: Components of Tinker Toy Assembly Task

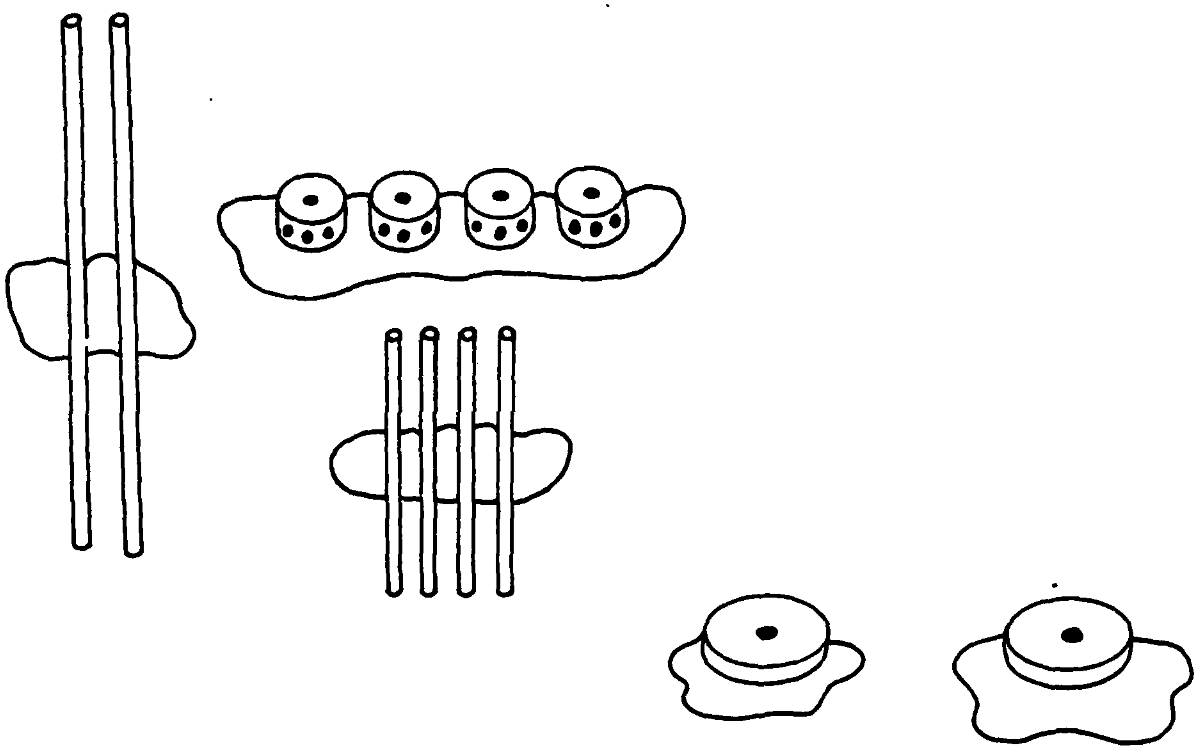
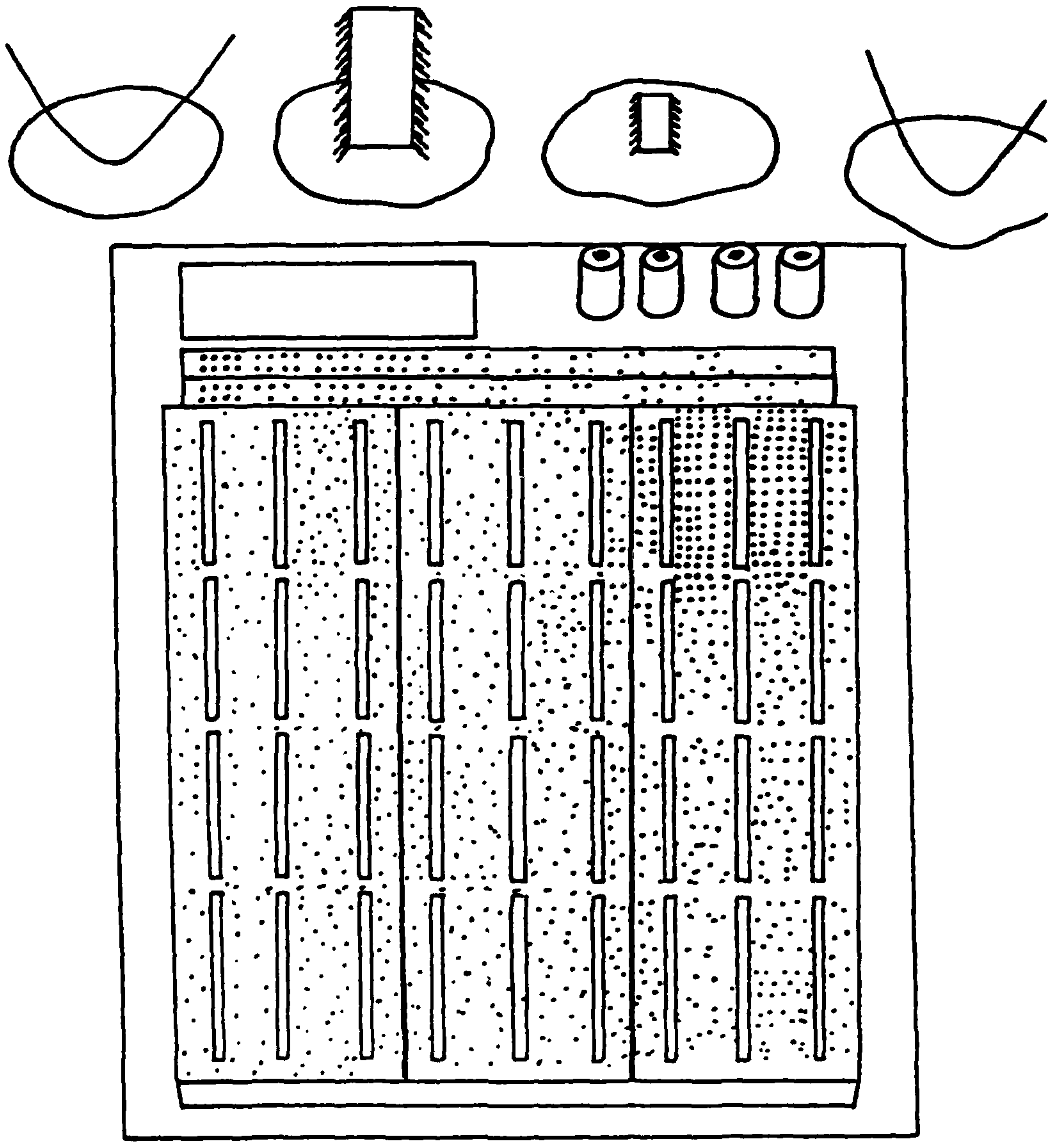


Figure 1-9: Components of Wire and Chip Insertion Assembly Task



Tables 1-2 through 1-6 (pages 26-30). Average assembly times for the second set (vision x dexterity) are shown in Tables 1-11 through 1-14 (pages 43-46). For each experimental condition, the average time is derived by taking each subject's median time for the five replications and then by averaging the median times of all five subjects. The standard deviation of each average time is also shown in the tables.

1.3 The Effects of Altering Levels of Vision and Taction on Task Performance Time

1.3.1 Two Levels of Vision Vs Four Levels of Taction

Average times required to assemble the devices with the two extreme levels of vision (sight, no sight) and four levels of taction (no gloves, light gloves, heavy gloves and wooden gloves) are are plotted in Figures 1-10 - 1-13 (pages 31-34).[7] Average time to complete the experiment is plotted on the horizontal axis. The four levels of taction are indicated on the vertical axis. Since we only distinguish between four qualitative levels of taction, the spacing on the vertical axis is arbitrary. The ordering of the levels of taction shown on the axis, with the level "no gloves" highest and the level "wooden gloves" lowest, is intentional since we believe that the amount of information transmitted via taction decreases as we shift from no gloves to light rubber gloves to heavy rubber gloves to wooden "gloves" (splints). The average assembly times for each level of vision are shown on a separate curve. Assembly times for experiments performed with full sight lie on the curve closer to the origin.

Given the graphs, the following items are of interest for each experiment:

1. For each level of vision, the percentage change in time resulting from a change in the level of taction (e.g. hold vision at full sight and change taction from no gloves to light gloves).

2. For each level of taction, the percentage change in time resulting from a change in the level of vision (e.g. hold taction at no gloves and change vision from full sight to no sight).

3. Whether or not these percentage changes are roughly the same across across all of the experiments.

4. Whether or not the curve of task performance time versus the level of taction with one level of vision parallel to the curve of time versus taction for other levels of vision.

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[7] A graph is not shown for the chip and wire insertion experiment because the results for the no sight case are not reported.

Full Sight and Varying Levels of Taction

For each level of vision, percentage changes in assembly times resulting from varying the level of taction are shown in Table 1-7 (page 35). Restating changes in assembly times in terms of percentage differences as opposed to absolute differences makes it possible to compare the differences across the various experiments. At the top of the table are the results obtained when subjects used full sight. At the bottom of the table are the results obtained when subjects were blindfolded (without sight).

With the use of full sight, the following regularities are apparent. Across all five of the assembly tasks, varying the hand covering from no gloves (NG) to light rubber gloves (LG) results in only a small percentage increase in assembly time, ranging from 3 to 15 percent. For four of the five tasks (excluding chip and wire insertion), Varying the hand covering from light rubber gloves to heavy rubber gloves (HG) results in a larger increase in assembly time, ranging from roughly 50 to 70 percent. Under these particular conditions, a restriction in the amount of tactile information available affects assembly performance in each of these experiments to about the same degree, even though each of the experiments are combinations of different types of assembly "subtasks".

The following irregularities are apparent. When the hand covering is shifted from LG to HG, assembly times for the chip and wire insertion are affected to a much larger degree than for the other experiments. As the subjects shift from HG to wooden gloves (WG)[8], the percentage changes vary widely across all the experiments. For chip and wire insertion, assembly time *decrease* by nearly 20 percent. For both the pencil sharpener and the nut and bolt, the percentage increase is about 3 times larger than the increase observed when varying the hand covering from LG to HG. For the tinker toy and flashlight, the percentage increase is less than the increase observed when varying taction from LG to HG. These results indicate that the extent of the effect of altering sensory information on task performance depends on the specific nature of the task (i.e. the particular composition of assembly subtasks comprising each experimental task).

There are exceptions to our generalization that performance in manipulative tasks improves with increasing amounts of sensory information processed. The time to insert the chips and wires into the circuit board decreases when the hand covering is changed from HG to WG. It is noted that while the wooden splint is assumed to transmit less tactile information to the subject than the heavy rubber glove, it is much stiffer (being nearly rigid). Apparently, when handling and positioning small, thin objects, such as chips and flexible wires, a rigid gripper, such as a wooden splint, gives the subject

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[8]These are actually wooden splints taped to the thumb and forefinger.

greater control than the bendable but bulky heavy rubber glove. It is proposed that in this case, the loss of tactile information is more than offset by the mechanical properties of the hand covering which somehow simplifies the information processing requirements of the task.

The effect of partially offsetting a decrease in tactile information with mechanical properties that increase dexterity in selected tasks might account for other irregularities. For the pencil sharpener and the nut and bolt, shifting the hand covering from HG to WG results in a percentage increase roughly a three times larger than the increase incurred when shifting from LG to HG. Apparently, varying the gripping surface from HG to WG substantially reduces the amount of tactile information transmitted to the hand, without providing any other advantages that would simplify the manipulative task despite the loss of information. For the flashlight and the tinker toy, the increase in time resulting from shifting the hand covering from HG to WG is less than the percentage increase when shifting from LG to HG. Apparently, for the flashlight and the tinker toy, varying the gripping surface from HG to WG still results in a substantial reduction in the amount of tactile information transmitted to the hand. However, because of the particular nature of these assembly tasks, the rigidity and shape of the wooden splints makes it easier to carry out particular assembly subtasks. The flashlight assembly requires that a thin round lens be grasped and positioned inside a lens hood. Our observations confirm that the lens is more easily grasped with the wooden splints then with heavy rubber gloves. Also, the thin, cylindrical shaped tinker toy rods are more easily grasped with the wooden splints than with the heavy rubber gloves. It appears that the loss of tactile information in these tasks is partially offset by properties of the wooden split that simplify the task of grasping thin parts. We think that the loss of information is not as critical here because of mechanical properties of the gripper which reduce the need for information processing. Thus, the time to assembly these devices with wooden splints is not substantially longer than the time required to assemble them with heavy rubber gloves.

No Sight and Varying Levels of Taction

The bottom half of Table 1-7 shows the percentage changes in assembly times when subjects perform the experiments without sight and the levels of taction are varied. The percent changes vary widely across the different experiments. The following irregularities are noted. When the hand covering is shifted from NG to LG, for the nut and bolt, assembly time decreases. For the pencil sharpener, assembly time increases only slightly. For the flashlight and the tinker toy, time increases by 30 to 50 percent. In contrast, with vision, shifting from NG to LG affected all experiments in roughly the same proportions. This difference between the results with sight and without sight shows that the impact of altering the input of tactile information on assembly time depends on the amount of visual information that is available. The chip and wire insertion provides the most extreme example of this point. With full sight, this experiment can be completed in finite time with all four hand coverings.

Without sight, none of the subjects were able to complete the task with any of the hand coverings.[9]

Shifting the hand covering LG to HG results in an increase from 60 to over 140 percent across the four experiments. Shifting from HG to WG results in a percentage increase for the nut and bolt and pencil sharpener that is several times larger than the increase observed when varying taction from LG to HG. For the flashlight and tinker toy, however, shifting from HG to WG results in a percentage increase that is less than the increase observed when varying taction from LG to HG for the flashlight and the tinker toy respectively. This same pattern was also observed when these experiments were performed with vision.

Without sight, the time to assemble the the nut and bolt is slightly less with light rubber gloves than with bare hands (no gloves).[10] The time to assemble the pencil sharpener sharpener is only slightly greater with light rubber gloves than with no gloves. For the flashlight and the tinker toy, however, assembly time with light rubber gloves is 30 to 50 percent larger than with no gloves. As noted earlier, with sight. assembly times for all four devices are slightly larger with with light rubber gloves than with bare hands. Without sight, the use of light rubber gloves has a negligible effect on assembly times for two devices, and results in a 30 to 50 percent increase for the two others.

It is noted that while the light weight rubber gloves impair the flow of tactile information to the hands, they have a textured "non-slip" surface on the finger tip area.[11] Also, detailed observations of recordings of the experimental trials show that without sight, wearing thin rubber gloves actually decreases the time required to grasp an object, except if the object is very thin. If the object is very thin, there is a slight increase in time required to grasp it compared to using bare hands. Both the flashlight and the tinker toy have one or more very thin components (the lens and the tinker toy connecting rods), whereas the pencil sharpener and the nut and bolt do not.

With this knowledge, the following explanation seems plausible. With vision, the operator would see the best way to grasp and hold an object. Once an object is in the hand of the operator, the grip need

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[9] The task required place the chips into a specific set of holes in a circuit board. Without sight the subjects could place the chip in the board, but not in the specified set of holes.

[10] The decrease is not significant, considering the standard deviations of the average assembly times without gloves (NG) and with light gloves (LG). Also, these average times were computed by taking the median of each subject's five trials and averaging the five median times across subjects. If each subject's five trials were averaged, and then the final average were computed from the five sets of averages, there would be a slight increase when the hand covering is shifted from no gloves to light gloves.

[11] These gloves are sold for washing kitchen ware. The fingertips of the gloves are "ruffled" to help prevent the slippage of wet dishes, cookery, and cutlery.

not be adjusted much so that the "non-slip" surface feature of the lightweight rubber glove is not utilized much. However, the thin rubber cover over the hand impairs the flow of tactile information enough so that some manipulative tasks involving tactile feedback are impaired and assembly time is increased. When the experiments are performed without vision, the operator can not see the best way to grasp and hold objects. To get the objects properly positioned in the hand, the operator has to make some adjustments, moving the object around until it "feels" as if it is in the proper position and orientation. Apparently, for the nut and bolt and pencil sharpener experiments, , the "non-slip" surface makes grasping easier enough to partially or fully offset the difficulties of having a slightly impaired sense of tactile feedback required for some of the other manipulative tasks.

For the flashlight and tinker toy, the difficulties associated with grasping and manipulating thin objects without vision somehow offsets the advantages of having the "non-slip" surface. Perhaps the added information processing requirements of needing to more precisely handle objects offsets the advantage of a surer grasp. Other important factors might be related to differences in the texture of the two sets of devices (both the lens and the connecting rods are nonmetallic) , or to some sub task in the assembly sequence that is present in the first two devices and not in the others.

While these particular differences are not easily explained, it is becoming clearer that the effect of changes in the amount of tactile information processed depends on the nature of the detailed task performed and on the level of visual information that is available.

Fixed Level of Taction and Varying Levels of Vision

Measuring the increase in assembly time resulting from the loss of visual information is another way of analyzing the experimental results. In Figures 1-10 through 1-13, this difference is given by the horizontal distance between the two sets of curves. The following observations are readily apparent from viewing the figures.

- The line segments for the "full sight" case and for the "no sight" case are not parallel with one another. This nonparallelism means the magnitude of the increase in assembly time resulting from a lose in visual information depends on the level of taction. This indicates that the impacts of changes in the levels of taction and in the level of vision are not independent of one another.

- This increase is always largest when the hand is covered with wooden gloves.

- For a given level of taction, the impact of losing visual information varies across the four experiments.

The percentage increases in time resulting from a loss of visual information are shown in Table

1-8 (page 36). Results are not shown for the chip and wire insertion.[12] Using NG, LG, and HG, the impact of shifting from full sight (FS) to no sight (NS) on assembly time varies widely across the four experiments. Thus, the impact depends on the nature of the assembly task. Using WG, shifting from full sight to no sight has the largest and a more uniform affect on assembly times across experiments. For three of the experiments, time increases by roughly a 340 percent and for the other, time increases by 280 percent.

For the nut and bolt, shifting from full sight to no sight results in only a relatively small time increase when using NG, LG, and HG to cover the hands. The increase with NG is larger than the increase using LG. This is a result of the decrease in time when the hand covering is shifted from NG to LG when the experiments are performed without vision. Apparently, for this type of screwing operation (threading a nut onto a bolt), the the removal of visual information does not result in a large time increase until wooden gloves are used. Our conclusion here is that as long as there is even a crude sense of taction (the amount corresponding to wearing heavy rubber gloves), the absence of visual information does not significantly impair performance. Yet, when tactile information is essentially removed (wooden splints are worn), the loss of visual information results in a large degradation in performance. This clearly shows that for this operation, the impact of removing visual information strongly depends on the level of tactile information that is available.

In contrast, for the tinker toy, losing visual information results in a large increase in assembly time even when using bare hands, as well as when using the other hand coverings. Assembling the tinker toy requires that each rod be "force fit" into the connector piece. Our observations show that with all of the hand coverings tested, the time required to perform the force fitting operation increases substantially when sight is lost. For this type of task, the loss of visual information is important at any level of taction, even though it is increasingly more important as the level of tactile information is reduced.

The pencil sharpener, flashlight and tinker toy all have multiple components and require a several different types of assembly subtasks. In this sense, these three devices are more complex to assemble than the nut and bolt. Understandably, for each level of taction, when visual information is lost, the percentage increase in time for these three devices is larger than for the nut and bolt. Even among the pencil sharpener, flashlight and tinker toy, there are interesting differences in the patterns of change. For the flashlight and tinker toy, the magnitude of the percentage increase resulting from

[12] With no gloves and light gloves, subjects could insert the chip and wire, but not into the prespecified positions on the circuit board. With heavy gloves and wooden splints, four of the five subjects could not even complete the insertion tasks.

the shift from sight to no sight increases monotonically moving from the highest level of taction (NG) to the lowest level (WG). Apparently, the less tactile information transmitted through the hands, the greater the impact of losing visual information. Also, for these two devices, the loss of visual information affects the heavy glove case to the same extent as the wooden glove case. For the pencil sharpener, the greatest increase in time for a loss in sight occurs with the lowest level of taction (WG), as with the flashlight and tinker toy. However, these changes do not steadily increase moving from NG to LG to HG. Also, the increase using HG is less than one half of that when using WG.

These examples highlight that different types of assembly subtasks require different types and amounts of sensory information processing. As a result, different assembly subtasks are affected by increases and decreases in visual and tactile information to different degrees. In some cases, adding additional sensory information of one type or another may result in a significant improvement in performance. In another case, it might not. Another generalization is that the extent of the impact of an increase in one type of sensory information processing on performance often depends on the amount of other types of information that are available, and the nature of the interdependence between different types of sensory information also depends on the nature of the assembly subtask.[13]

1.3.2 Four Levels of Sight Vs Four Levels of Taction

Subjects also performed the assembly experiments while looking through a gauze bandage (gauze bandage blinders or GB) and through wax paper (wax paper blinders or WB). These intermediate levels of vision, between the extremes of full sight and no sight, are used to test what happens to assembly time when visual input is partially, but not fully constrained. As with the levels of taction, we can only qualitatively distinguish between the four levels of vision. Nonetheless, we believe that the amount of visual information transmitted to the subject via sight decreases as we shift from full sight to gauze bandages to wax paper to no sight.

Average times to assemble each devices under the 16 conditions (4 levels of vision x 4 levels of taction) are plotted in Figures 1-14 through 1-17 (pages 37-40). The results for each of the four levels of vision are shown on a separate curve within the figure. The curves for the cases of "full sight" and "no sight" are the same as those discussed earlier in Figures 1-10 through 1-13. The other two curves add the results for the two intermediate levels of vision.

For the pencil sharpener and the tinker toy (Figures 1-14 and 1-17), there are no exceptions to the pattern of assembly time increasing as sensory information is restricted. For each level of taction,

[13] An analysis of variance supports the assertion of an interaction between the levels of visual and tactile information.

assembly time increases as the level of vision is restricted from full sight to gauze bandages to wax paper to no sight. Also, for each level of vision, assembly time increases as the level of taction decreases from NG to LG to HG to WG. With the nut and bolt and the flashlight, there are several exceptions to the pattern of assembly time increasing as the amount of sensory information is restricted. This is especially evident where the curves for the different levels of vision cross one another.

For each of the two additional levels of vision, the percentage changes in assembly time resulting from varying the level of taction are shown in Table 1-9. Results obtained when subjects looked through the gauze bandage are shown at the top of the table. Results obtained when subjects looked through wax paper are shown at the bottom. For the flashlight, with the level of sight fixed at wax blinders (WB), assembly time with light gloves is slightly less than the time without gloves (Table 1-9). The decrease is not significant, given the standard deviations on these times.[14] With the tinker toy, the percentage increase in time when shifting from LG to HG is respectively equal to and larger than the increase when shifting from HG to WG when vision is fixed at the levels of gauze blinders and wax blinders. With these exceptions, the impact of restricting tactile information increases in the other experiments as subjects shift from NG to LG to HG to WG. For all of the devices, the largest proportional increase in time occurs when shifting from HG to WG.

For the two intermediate levels of vision, the interaction between the levels of vision and taction does not appear to be as strong as the interaction when only the two extreme levels of vision are used. In Figures 1-14 - 1-17, one can see that the line segments for gauze blinders and wax paper are more parallel with each other then the line segments for the cases of no sight and full sight. Also, the percentage changes in Table 1-9 show that for each device, the impact of shifting from one level of taction to another is not much different across the two intermediate levels of vision.[15] For each level of taction, the percentage change in time resulting from shifting the level of visual input from one level to the next is shown in Table 1-10. For each device, instances where the curve for one level of vision intersects the curve for another level are easily detected in the table by minus signs. In these several cases, for a given level of taction, it takes longer to assembly a device with presumably "more" visual information than with "less" visual information. This occurs twice in the nut and bolt experiment (with

[14] If the average times were computed from the average of each subject's five trials, as opposed to the mean of each subject's trials, there would be a slight increase when shifting from no gloves to light gloves.

[15] The observation that there is a higher degree of parallelism between the curves for gauze blinders and wax blinders than between the curves for full sight and no sight is supported by an analysis of variance. For each experiment, the probability that the interaction term between vision and taction is significant is smaller when comparing gauze blinders and wax blinders than when comparing full sight and no sight.

LG and HG) and once in the flashlight experiment (with HG). However, the decreases in time are only slight, and may be the result of random experimental variation.[16] Earlier, several cases were discussed where, with a given level of vision, assembly time with presumably "more" tactile information was greater than with "less" tactile information. In these exceptional cases, it was proposed that the loss of tactile information was offset by another feature of the hand covering, such as its rigidity or surface friction, that simplified the grasping and/or manipulating of the part. When the level of taction is held constant and the level of vision is varied, it does not seem reasonable to argue that a loss information input is offset by another property of the visual sense that simplifies the manipulative task. After all, vision is a <u>non</u>contact type of sensing, as opposed to taction, which requires direct physical contact with an object.

1.4 The Effects of Altering Levels of Vision and Dexterity on Task Performance Times

The human capabilities jointly examined here are vision and dexterity. By dexterity, we mean mean the number of fingers used by the subject to assemble the device.[17] Dexterity is controlled at three levels: two hands, one hand and two fingers. We assume that the subject's capability decreases as the number of number of fingers is reduced from the numbers corresponding to two hands, one hand, and two fingers. One reason for this assumption is that it is easier to manipulate objects with more degrees of freedom than with fewer, given that normal functioning humans have well developed motor control. In addition, assuming that each finger can transmit roughly the same amount of tactile information, reducing the number of fingers used to assemble (from 10 to 5 to 2) also reduces the amount of tactile information transmitted. For these experiments, the level of vision is controlled at two levels: full sight and no sight. The nut and bolt experiment was not performed under these conditions.

The average times required to assemble the pencil sharpener, flashlight, tinker toy and wire and chip for the different levels of vision and dexterity are shown in Tables 1-11 through 1-14 (pages 43-46).[18] These times are plotted in Figures 1-18 through 1-20 (pages 47-49).[19] Percent changes in

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[16] In all three of these cases, if the average times were computed from the average of each subject's five trials, as opposed to the mean of each subject's trials, there would be a slight increase in time when shifting from the "higher" level of visual information to the "lower" one.

[17] Another way to think about levels of dexterity are the number of degrees of freedom used in the subject's hands.

[18] For the wire and chip insertion experiment, the results are not shown for the no sight case. Without sight, the subjects could insert the components, but not into the specified holes in the circuit board.

[19] A plot is not shown for the wire and chip insertion experiment, since only the times for the full sight case are reported.

time resulting from varying one capability while holding the other constant are shown in Tables 1-15 and 1-16 (pages 50-51). Not surprisingly, for a given level of dexterity, the assembly time without sight is larger than with sight. Also for a given level of vision, the assembly time increases as the level of dexterity is decreased from two hands to one hand to two fingers. These results also show that the time required to perform a task is inversely related to the amount of sensory information available to the subject.

The percent increases in time resulting from shifting from one level of dexterity to another, for a fixed level of vision, are shown in Table 1-15. At the top of the table are the results when vision is fixed at full sight. At the bottom are the results when vision is fixed at no sight. For two of the devices, shifting from two hands to one hand affects the assembly time to a greater degree when subjects have full sight than when they are blindfolded. The percentage time increase is larger with full sight than with no sight for the flashlight and tinker toy. For the pencil sharpener, the percentage increase is larger when the subjects are blindfolded. When the level of dexterity is shifted from one hand to two fingers, assembly times for the three devices are affected by a greater percentage when the subjects are blindfolded then when they have full sight. For the flashlight and the tinker toy, the percentage change for the no sight case is many times that of the full sight case. For the pencil sharpener, the difference between the two cases is not nearly as large. For the pencil sharpener, flashlight, and tinker toy, there appears to be an interaction between the capabilities of vision and dexterity since a change in the level of dexterity affects performance with sight and without sight to different degrees.[20]

The percentage change in assembly time when vision is changed from full sight to no sight is shown in Table 1-16 (page 51) for each level of dexterity. When sight is eliminated, the percentage increase in assembly times while using one hand is smaller than the increase while using two hands for the flashlight and tinker toy. For the pencil sharpener, the increase while using two hands is slightly smaller than the increase while using one hand. Not surprisingly, for each device, when there is a loss of vision, assembly times for the lowest level of dexterity, two fingers, increase by the largest percentage. This is a similar result to the earlier experiments where, in most instances, assembly times for the lowest level of taction (wooden gloves) were affected the most when vision was reduced from full sight to no sight. It also apparent that the the impact of shifting from full sight to no sight varies widely across the devices. For each level of dexterity, the the percentage increase is smaller for the flashlight than for the pencil sharpener and the tinker toy. We have no explanation of why

[20] An analysis of variance supports the assertion of an interaction between vision and dexterity in each of these three experiments.

dexterity (and taction) apparently compensates for more of the loss of visual information in the case of the flashlight than in the case of pencil sharpener and tinker toy.

Why does a loss of vision affect performance with two fingers more than with one hand? One plausible explanation is that one hand--with five "sensing" fingers transmitting tactile information--provides more information to the subject than only two fingers and makes it easier to compensate for a loss of visual information. Such an explanation is consistent with our experiment results obtained when varying the levels of vision and taction. There is also the factor that using one hand provides more degrees of freedom than two fingers for manipulation. These reasons would suggest that using two hands for assembly would provide more tactile information and mechanical degrees of freedom than using one hand. When visual information is eliminated, we would suspect that it would be easier to compensate using two hands, and that times for two handed assembly would be affected less than those for one handed assembly. The experimental results show the opposite effect occurs for the flashlight and tinker toy. Our proposed reasons do not explain why, for these two devices, assembly times with two hands increase by a greater percentage than time with one hand when vision is eliminated. One suggestion is that without sight there may be difficulties in coordinating two hands that are not encountered when only one hand is used. This issue warrants further investigation.

1.5 Assembly Times and Percent Change in Times: Tables and Figures

All tables and figures referenced in sections 1.3.1, 1.3.2 and 1.4 are presented in the following pages.

Table 1-2: Average Times to Assemble Pencil Sharpener with Different Levels of Vision and Taction

LEVELS OF TACTION	LEVELS OF VISION: Full Sight (FS)	Gauze Blinders (GB)	Wax Blinders (WB)	No Sight (NS)
No Gloves (NG)	9.8 (2.2)	11.8 (2.0)	19.6 (2.6)	29.9 (13.8)
Light Rubber Gloves (LG)	10.6 (2.2)	13.0 (4.6)	27.6 (15.9)	30.0 (19.3)
Heavy Rubber Gloves (HG)	16.2 (8.0)	17.4 (8.0)	44.2 (9.2)	59.1 (43.8)
Wooden "Gloves" (splints) (WG)	43.4 (16.2)	74.0 (25.1)	162.0 (99.9)	192.8 (107.5)

Average time = $(1/5)\sum_{i=1}^{5} t_i$

t_i = median time of five assembly trials for subject i

5 subjects

( ) = standard deviation of average time

Table 1-3: Average Times to Assemble Nut and Bolt with Different Levels of Vision and Taction

LEVELS OF TACTION	LEVELS OF VISION			
	Full Sight (FS)	Gauze Blinders (GB)	Wax Blinders (WB)	No Sight (NS)
No Gloves (NG)	5.6 (0.5)	6.2 (1.3)	7.0 (1.4)	7.0 (1.6)
Light Rubber Gloves (LG)	6.2 (0.4)	6.8 (0.8)	8.0 (1.6)	6.8 (0.8)
Heavy Rubber Gloves (HG)	9.8 (2.8)	13.8 (3.3)	13.4 (2.1)	16.6 (4.3)
Wooden "Gloves" (splints) (WG)	25.6 (7.9)	41.0 (10.1)	42.8 (14.8)	97.0 (70.9)

Average time = $(1/5)\sum_{i=1}^{5} t_i$

t_i = median time of five assembly trials for subject i

5 subjects

( ) = standard deviation of average time

Table 1-4: Average Times to Assemble Flashlight with Different Levels of Vision and Taction

LEVELS OF TACTION	LEVELS OF VISION			
	Full Sight (FS)	Gauze Blinders (GB)	Wax Blinders (WB)	No Sight (NS)
No Gloves (NG)	14.0 (4.2)	15.4 (3.0)	22.6 (4.4)	28.4 (5.6)
Light Rubber Gloves (LG)	14.4 (4.6)	15.8 (3.3)	20.6 (2.7)	44.4 (27.0)
Heavy Rubber Gloves (HG)	24.8 (10.6)	23.5 (9.1)	39.2 (6.1)	102.4 (51.9)
Wooden "Gloves" (splints) (WG)	33.6 (8.6)	40.2 (12.7)	89.2 (16.1)	149.8 (74.1)

Average time = $(1/5)\sum_{i=1}^{5} t_i$

t_i = median time of five assembly trials for subject i

5 subjects

( ) = standard deviation of average time

Table 1-5: Average Times to Assemble Tinker Toy with Different Levels of Vision and Taction

LEVELS OF TACTION	LEVELS OF VISION			
	Full Sight (FS)	Gauze Blinders (GB)	Wax Blinders (WB)	No Sight (NS)
No Gloves (NG)	29.0 (2.9)	47.0 (7.4)	72.8 (14.8)	101.4 (38.5)
Light Rubber Gloves (LG)	31.6 (3.9)	51.0 (5.9)	106.4 (34.5)	132.4 (53.3)
Heavy Rubber Gloves (HG)	50.0 (21.1)	74.8 (23.2)	136.4 (33.3)	213.0 (73.9)
Wooden "Gloves" (splints) (WG)	77.0 (30.6)	109.8 (30.6)	228.0 (64.5)	340.0 (163.2)

Average time = $(1/5)\sum_{i=1}^{5} t_i$

t_i = median time of five assembly trials for subject i

5 subjects

( ) = standard deviation of average time

Table 1-6: Average Times to Assemble Chip and Wire Insertion With Different Levels of Vision and Taction

LEVELS OF TACTION	LEVELS OF VISION			
	Full Sight (FS)	Gauze Blinders (GB)	Wax Blinders (WB)	No Sight (NS)
No Gloves (NG)	20.0 (1.6)	*	*	*
Light Rubber Gloves (LG)	23.1 (3.2)	*	*	*
Heavy Rubber Gloves (HG)	61.0 (15.4)	*	*	*
Wooden "Gloves" (splints) (WG)	48.0 (7.9)	*	*	*

Average time = $(1/5)\sum_{i=1}^{5} t_i$

t_i = median time of five assembly trials for subject i

5 subjects

( ) = standard deviation of average time

*: Experiments could not be completed accurately by subjects.

Figure 1-10: Pencil Sharpener: Average Assembly Time Vs Vision (Full Sight/No Sight) and Taction

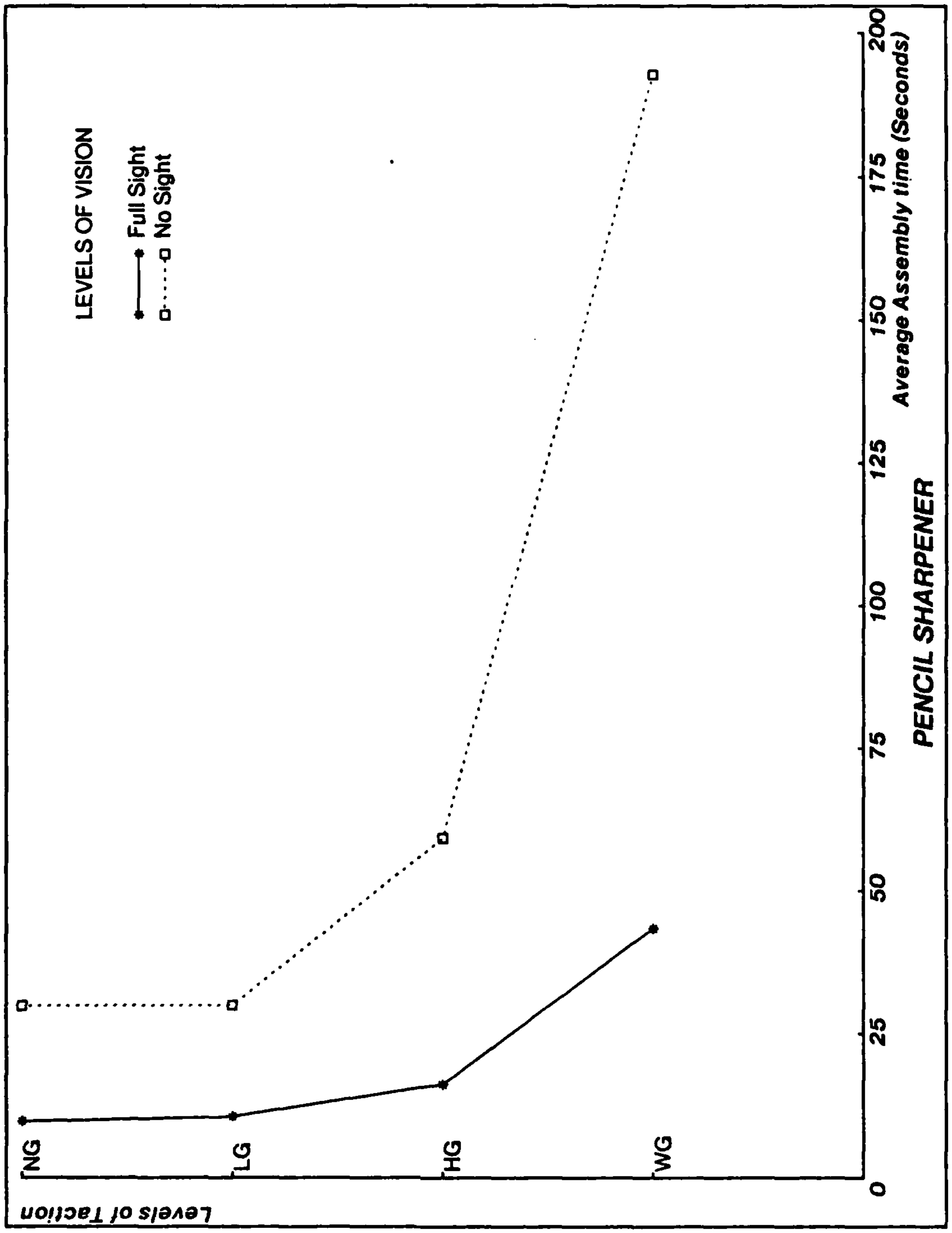

Figure 1-11: Nut and Bolt: Average Assembly Time Vs Vision (Full Sight/No Sight) and Taction

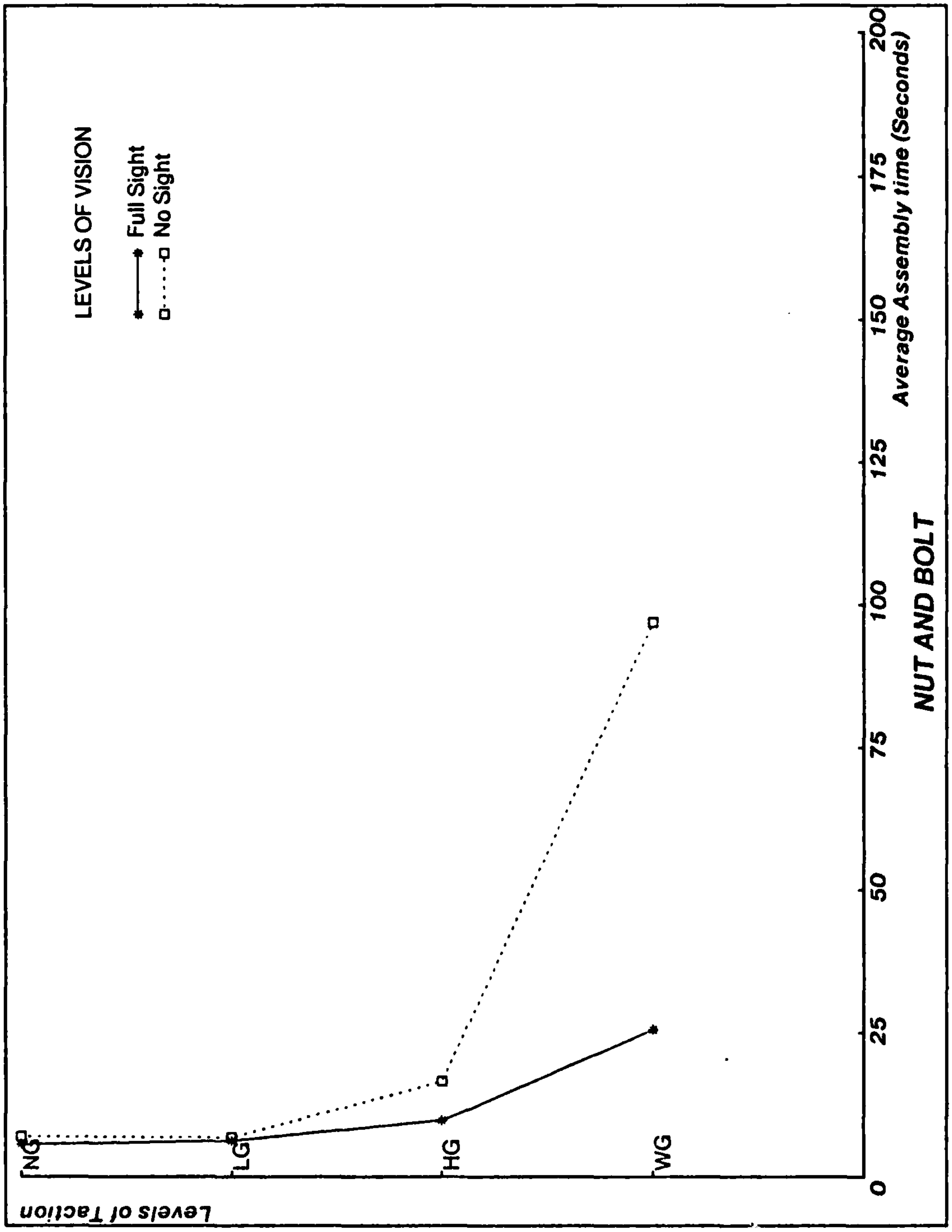

Figure 1-12: Flashlight: Average Assembly Time Vs Vision (Full Sight/No Sight) and Taction

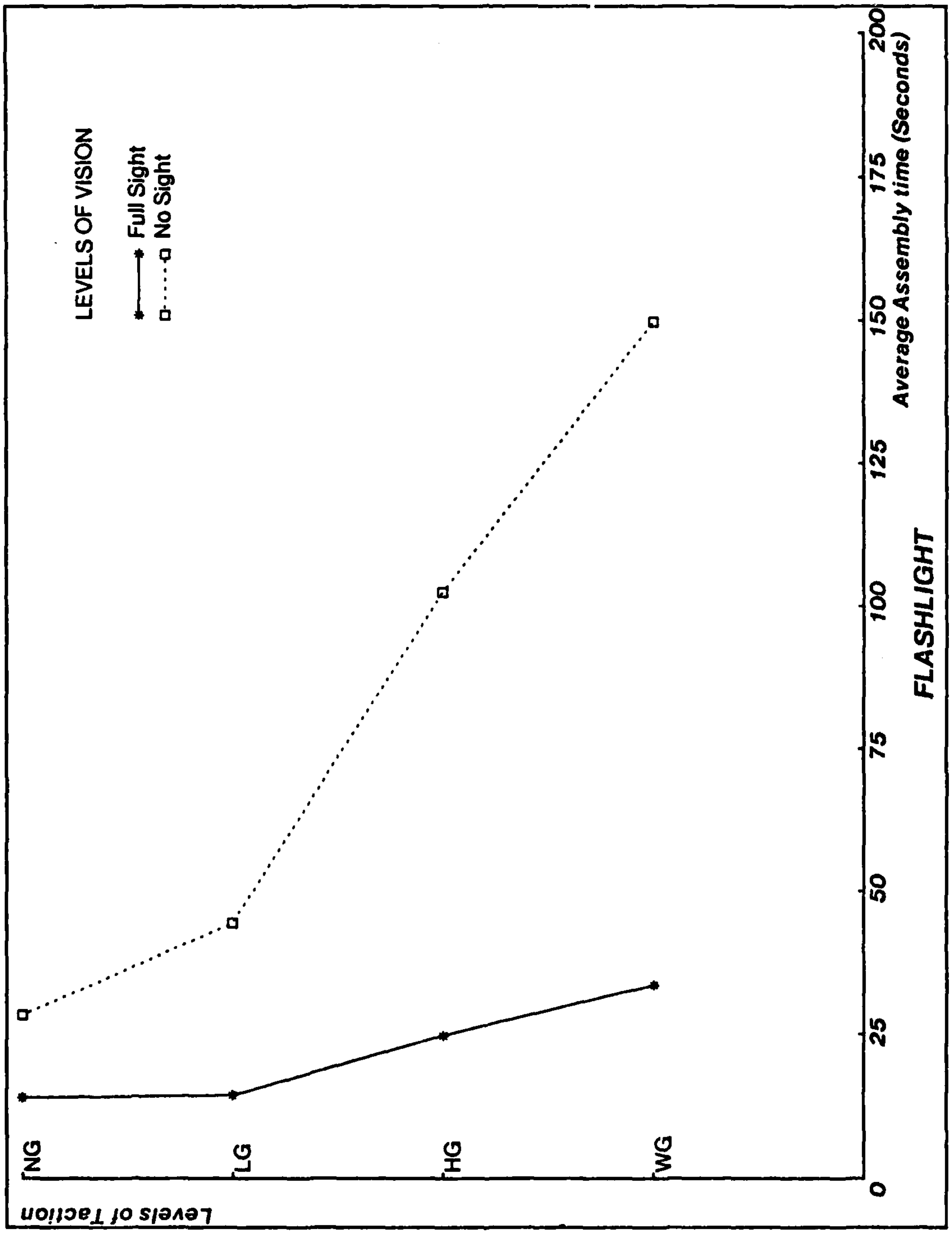

Figure 1-13: Tinker Toy: Average Assembly Time Vs Vision (Full Sight/No Sight) and Taction

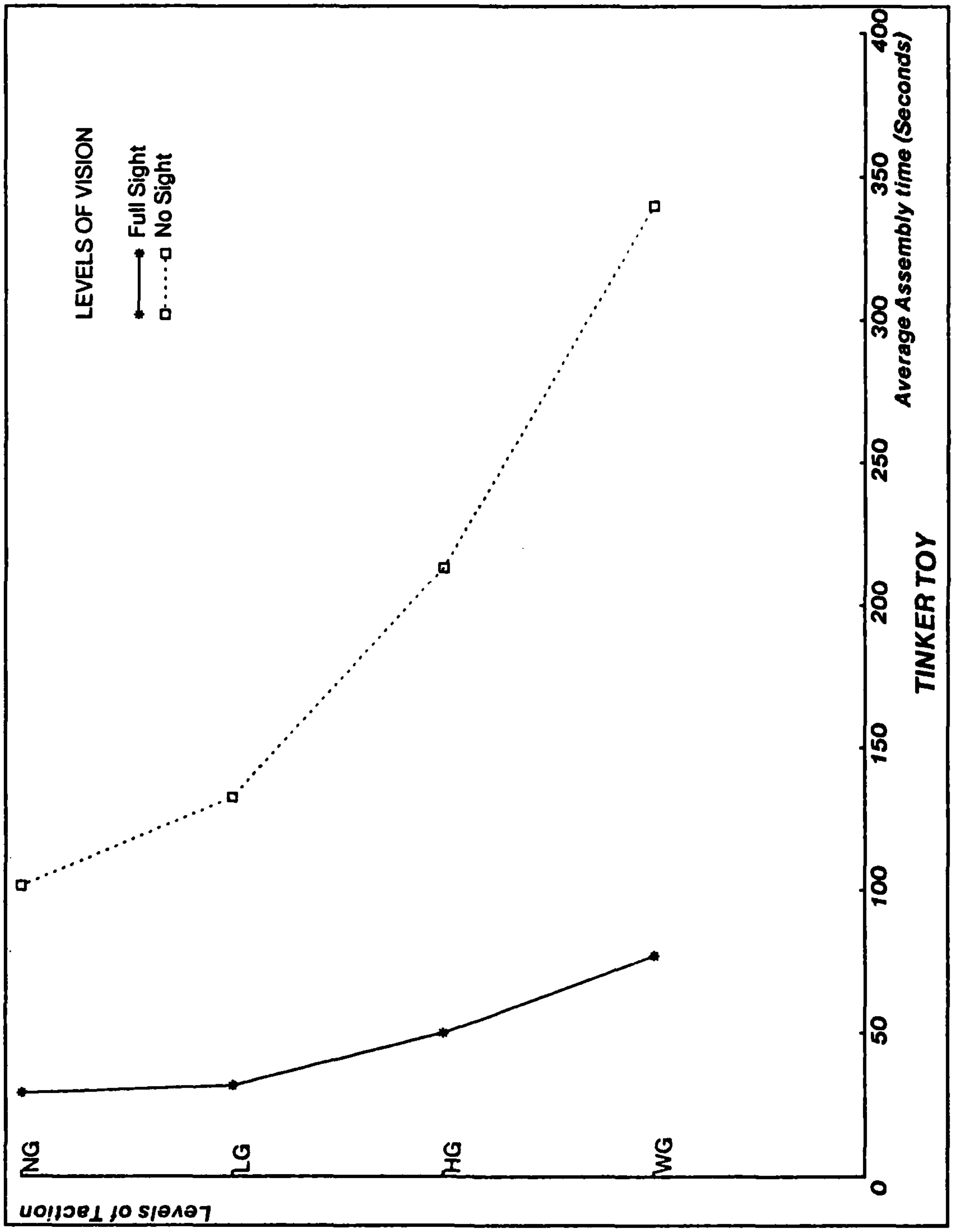

Table 1-7: Percent Change in Average Assembly Times:
Level of Vision Fixed at Full Sight or No Sight;
Level of Taction Varying

LEVEL OF VISION: FULL SIGHT

Change in Level of Taction From:	Percent Change in Average Assembly Time: P.S.	N. & B.	F.L.	T.T.	C. & W.
NG to LG	8	11	3	9	15
LG to HG	53	58	72	58	165
HG to WG	168	161	56	59	-21

LEVEL OF VISION: NO SIGHT

Change in Level of Taction From:	P.S.	N. & B.	F.L.	T.T.	C. & W.
NG to LG	0.3	-3	56	31	*
LG to HG	97	144	131	61	*
HG to WG	2260	484	46	60	*

*) experiments could not be completed accurately.

NG: No gloves (bare hands)
LG: Light weight rubber dish washing gloves
HG: Heavy weight rubber work gloves
WG: Wooden "gloves" (splints)

Note: all experiments performed with two fingers (the thumb and forefinger).

Table 1-8: Percent Change in Assembly Times:
Level of Taction Fixed; Level of Vision Varying from Sight to No Sight

	Percent Change in Assembly Time:				
	P.S.	N. & B.	F.L.	T.T.	C. & W.
TACTION LEVEL: NO GLOVES					
FS to NS	205	25	103	250	*
TACTION LEVEL: LIGHT GLOVES					
FS to NS	183	10	208	319	*
TACTION LEVEL: HEAVY GLOVES					
FS to NS	265	69	313	326	*
TACTION LEVEL: WOODEN GLOVES					
FS to NS	344	278	346	342	*

*: Experiments could not be completed accurately by subjects.

FS: full sight
NS: no sight (blindfolded)

Note: all experiments performed with two fingers (the thumb and forefinger).

Figure 1-14: Pencil Sharpener: Average Assembly Time Vs Vision (4 levels) and Taction

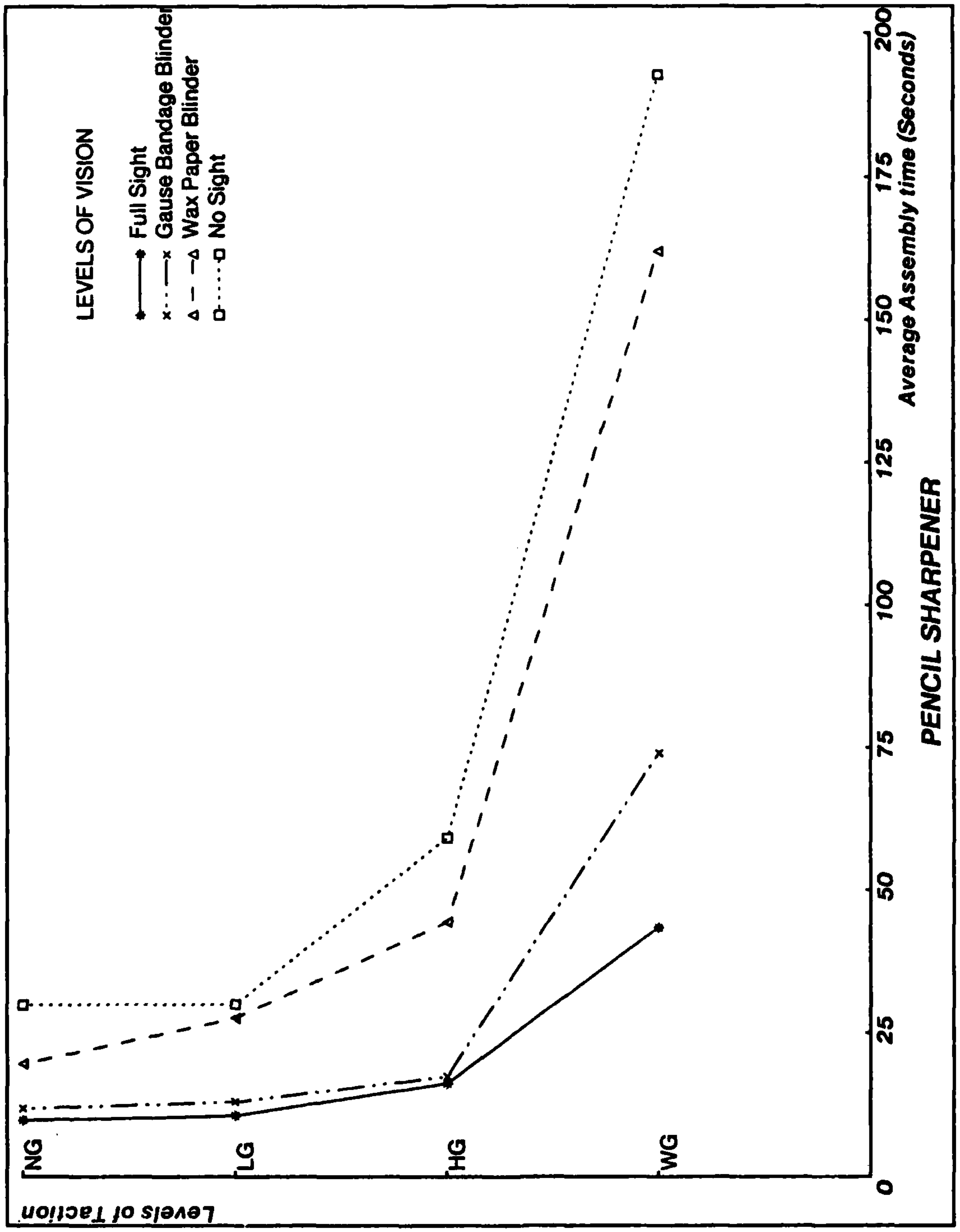

Figure 1-15: Nut and Bolt: Average Assembly Time Vs Vision (4 levels) and Taction

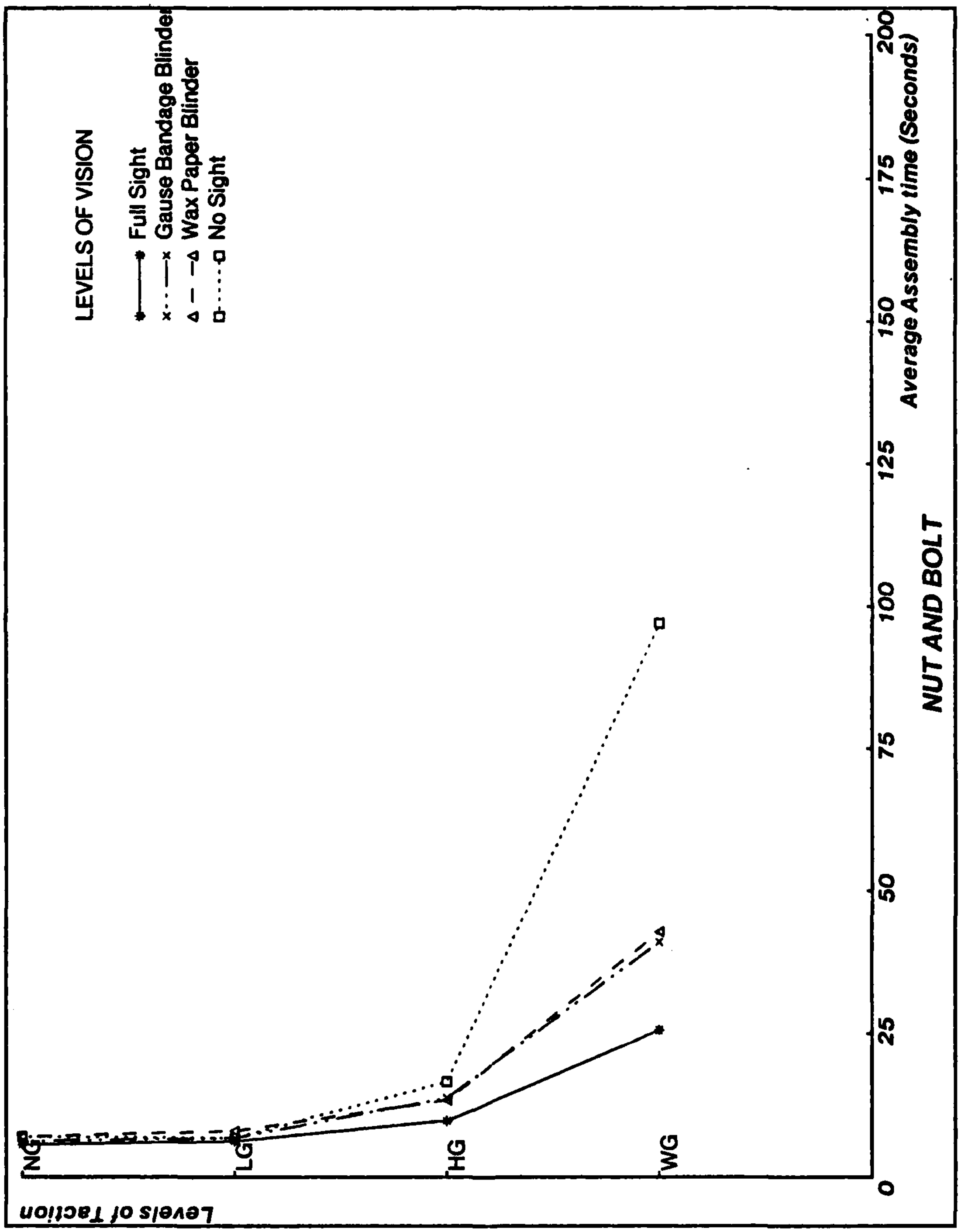

Figure 1-16: **Flashlight: Average Assembly Time Vs Vision (4 levels) and Taction**

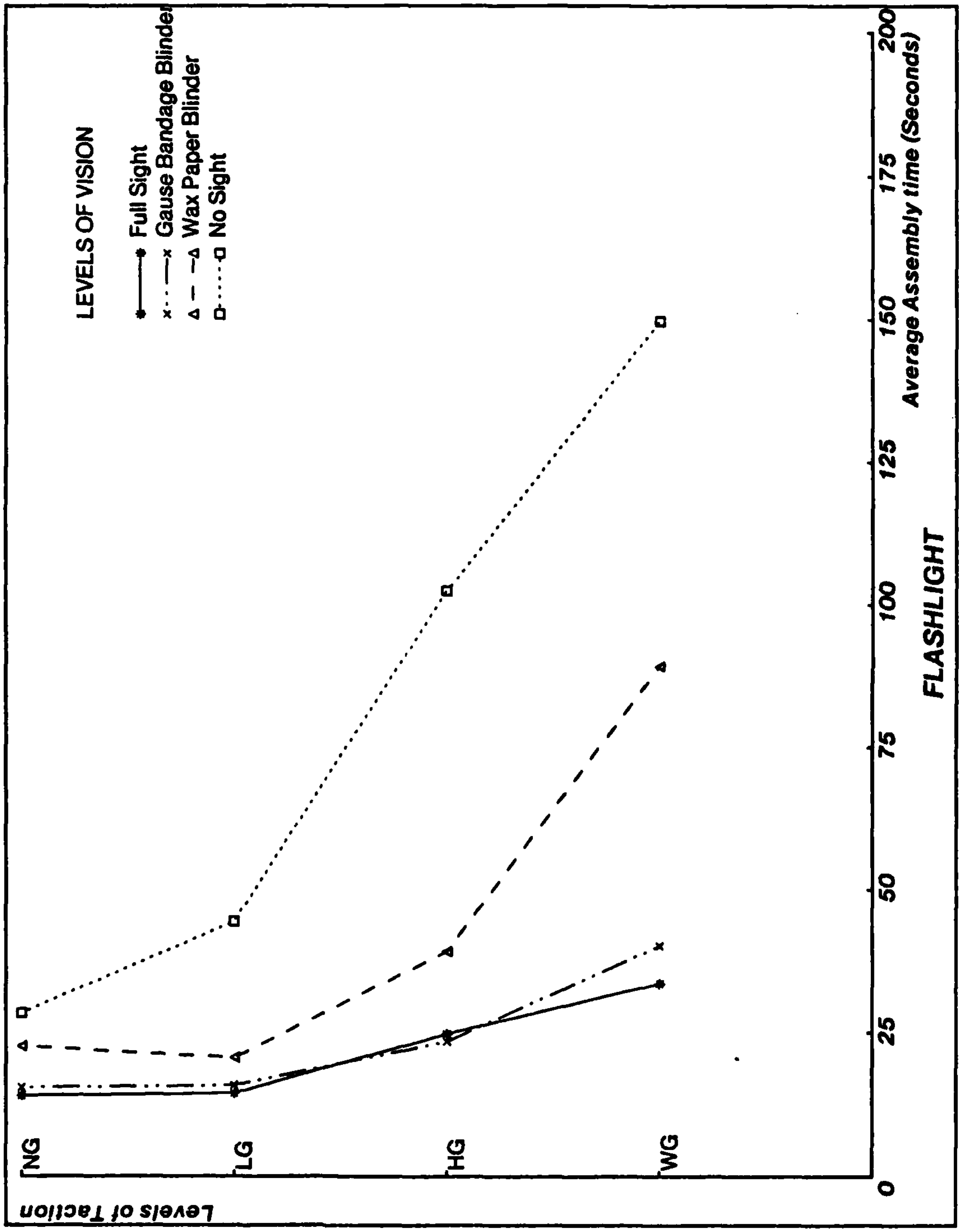

Figure 1-17: Tinker Toy: Average Assembly Time Vs Vision (4 levels) and Taction

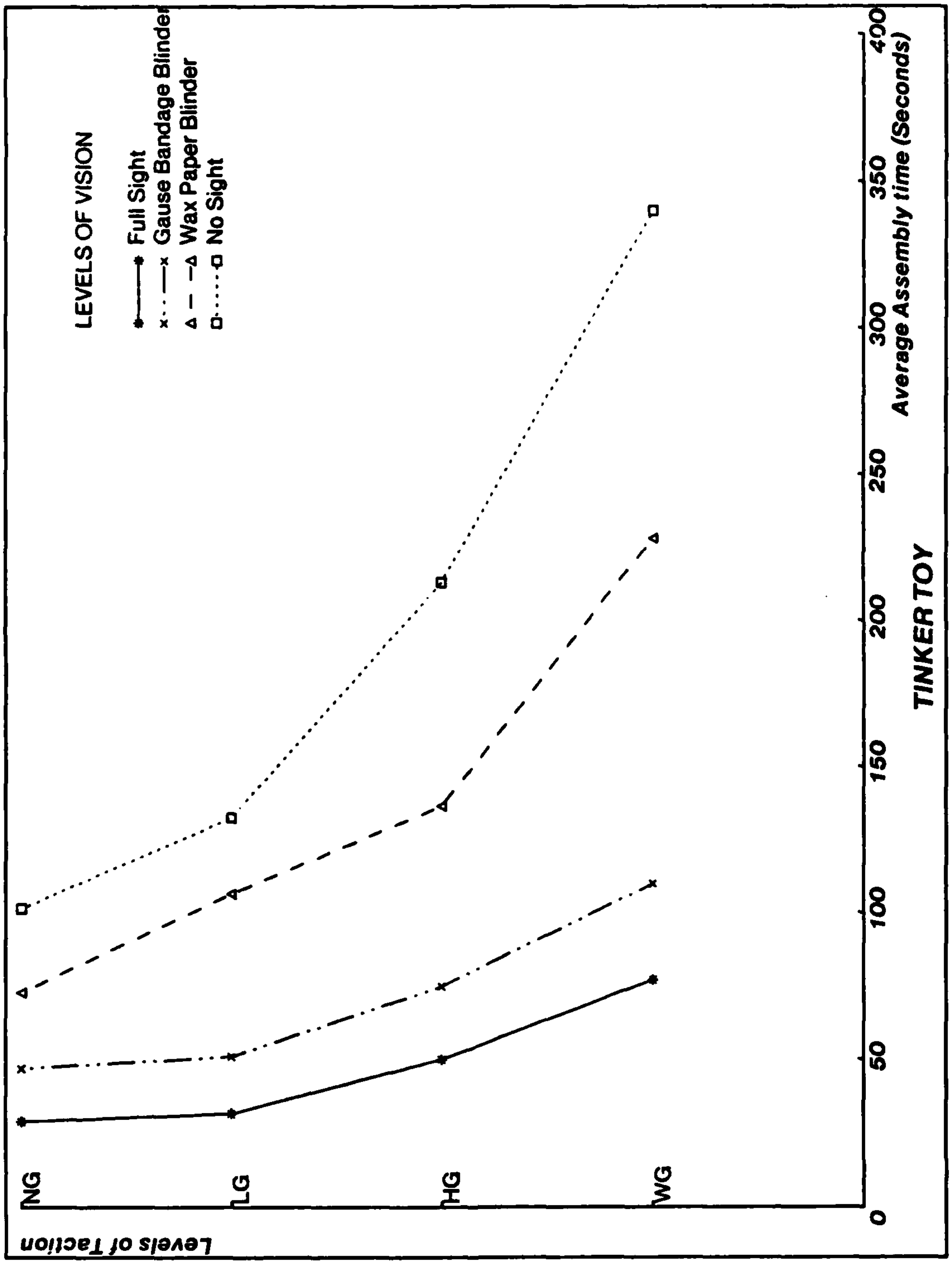

Table 1-9: Percent Change in Average Assembly Times:
Level of Vision Fixed at Intermediate Levels; Level of Taction Varying

LEVEL OF VISION: LOOKING THROUGH A GAUZE BANDAGE BLINDER

Change in Level of Taction From:	Percent Change in Average Assembly Time: P.S.	N. & B.	F.L.	T.T.	C. & W.
NG to LG	10	9	3	8	*
LG to HG	16	103	49	47	*
HG to WG	325	197	73	47	*

LEVEL OF VISION: LOOKING THROUGH A WAX PAPER BLINDER

Change in Level of Taction From:	P.S.	N. & B.	F.L.	T.T.	C. & W.
NG to LG	41	14	-9	46	*
LG to HG	61	67	90	28	*
HG to WG	265	217	127	67	*

Note: Percentage changes for Full Sight and No Sight given in Table 1-7.

*: Experiments could not be completed accurately by subjects.

NG: No gloves (bare hands)
LG: Light weight rubber dish washing gloves
HG: Heavy weight rubber work gloves
WG: Wooden "gloves" (splints)

Note: all experiments performed with two fingers (the thumb and forefinger).

Table 1-10: Percent Change in Assembly Times:
Level of Taction Fixed; Level of Vision Varying Over Four Levels

	Percent Change in Assembly Time:				
	P.S.	N. & B.	F.L.	T.T.	C. & W.
TACTION LEVEL: NO GLOVES					
FS to GB	20	11	10	62	*
GB to WB	66	13	47	55	*
WB to NS	53	0	26	39	*
TACTION LEVEL: LIGHT GLOVES					
FS to GB	23	10	10	62	*
GB to WB	112	18	30	109	*
WB to NS	9	-15	116	24	*
TACTION LEVEL: HEAVY GLOVES					
FS to GB	7	41	-5	49	*
GB to WB	155	-3	67	82	*
WB to NS	34	24	161	56	*
TACTION LEVEL: WOODEN GLOVES					
FS to GB	71	60	20	43	*
GB to WB	119	4	122	108	*
WB to NS	19	127	68	49	*

FS: full sight

GB: looking through gauze bandage blinder

WB: looking through wax paper blinder

NS: no sight (blindfolded)

*: Experiments could not be completed accurately by subjects.

Table 1-11: Average Time to Assemble Pencil Sharpener with Different Levels of Vision and Dexter

LEVELS OF DEXTERITY	LEVELS OF VISION	
	Full Sight FS	No
2 Hands (2H)	8.8 (2.9)	18.8 (5.6)
1 Hand (1H)	12.6 (2.7)	30.9 (11.0)
2 Fingers (2F)	15.2 (3.0)	45.5 (13.4)

$$\text{Average time} = (1/5)\sum_{i=1}^{5} t_i$$

t_i = median time of five assembly trials for subject i

5 subjects

( ) = standard deviation of average time

Table 1-12: Average Time to Assemble Flashlight with Different Levels of Vision and Dexterity

LEVELS OF DEXTERITY	LEVELS OF VISION	
	Full Sight FS	No Sight NS
2 Hands (2H)	9.8 (1.6)	17.0 (2.8)
1 Hand (1H)	17.0 (7.3)	21.6 (6.3)
2 Fingers (2F)	17.4 (4.5)	34.8 (9.1)

Average time = $(1/5)\sum_{i=1}^{5} t_i$

t_i = median time of five assembly trials for subject i

5 subjects

( ) = standard deviation of average time

Table 1-13: Average Time to Assemble Tinker Toy with Different Levels of Vision and Dexterity

LEVELS OF DEXTERITY	LEVELS OF VISION	
	Full Sight FS	No Sight NS
2 Hands (2H)	24.8 (1.3)	60.4 (7.4)
1 Hand (1H)	39.0 (18.0)	76.6 (25.4)
2 Fingers (2F)	41.0 (5.7)	125.0 (34.6)

Average time = $(1/5)\sum_{i=1}^{5} t_i$

t_i = median time of five assembly trials for subject i

5 subjects

( ) = standard deviation of average time

Table 1-14: Average Time to Assemble Wire and Chip Insertion with Different Levels of Vision and Dexterity

LEVELS OF DEXTERITY	LEVELS OF VISION	
	Full Sight FS	No Sight NS
2 Hands (2H)	21.2 (4.8)	*
1 Hand (1H)	22.0 (5.7)	*
2 Fingers (2F)	27.0 (3.7)	*

Average time = $(1/5)\sum_{i=1}^{5} t_i$

t_i = median time of five assembly trials for subject i

5 subjects

( ) = standard deviation of average time

*: Experiments could not be completed accurately by subjects.

Figure 1-18: Pencil Sharpener: Average Assembly Time Vs Vision (Full Sight/No Sight) and Dexterity

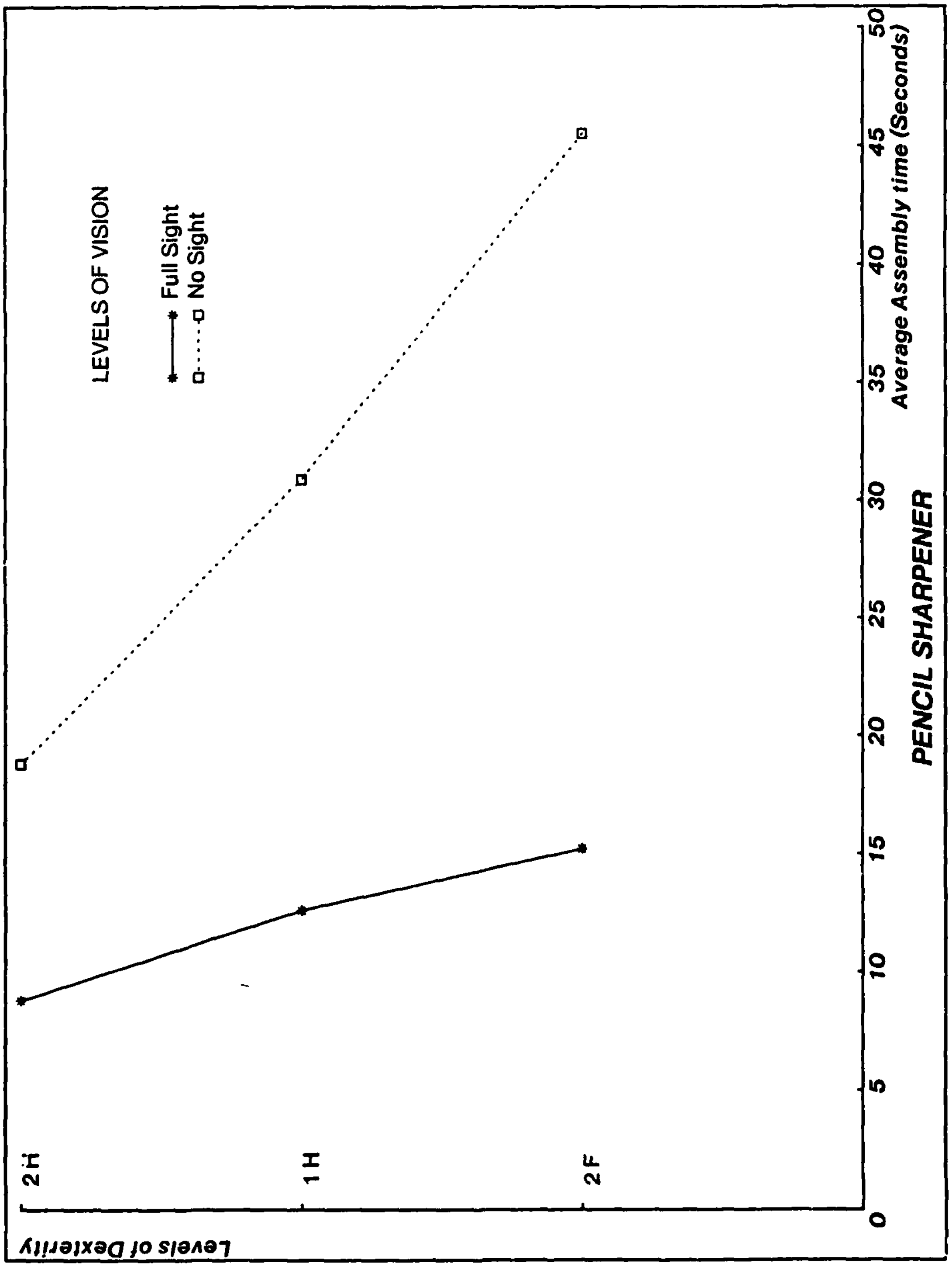

Figure 1-19: Flashlight: Average Assembly Time Vs Vision (Full Sight/No Sight) and Dexterity

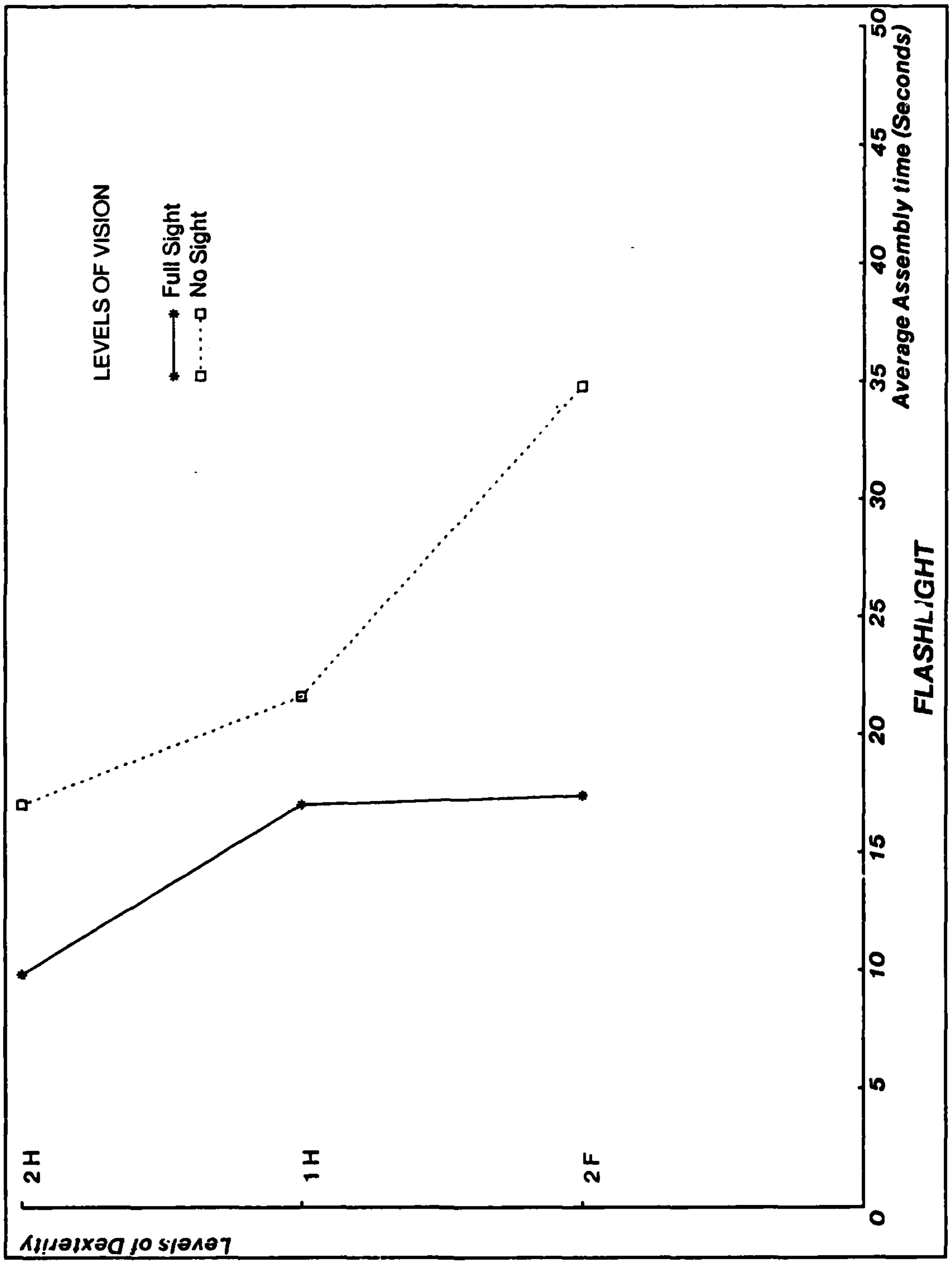

Figure 1-20: Tinker Toy: Average Assembly Time Vs Vision (Full Sight/No Sight) and Dexterity

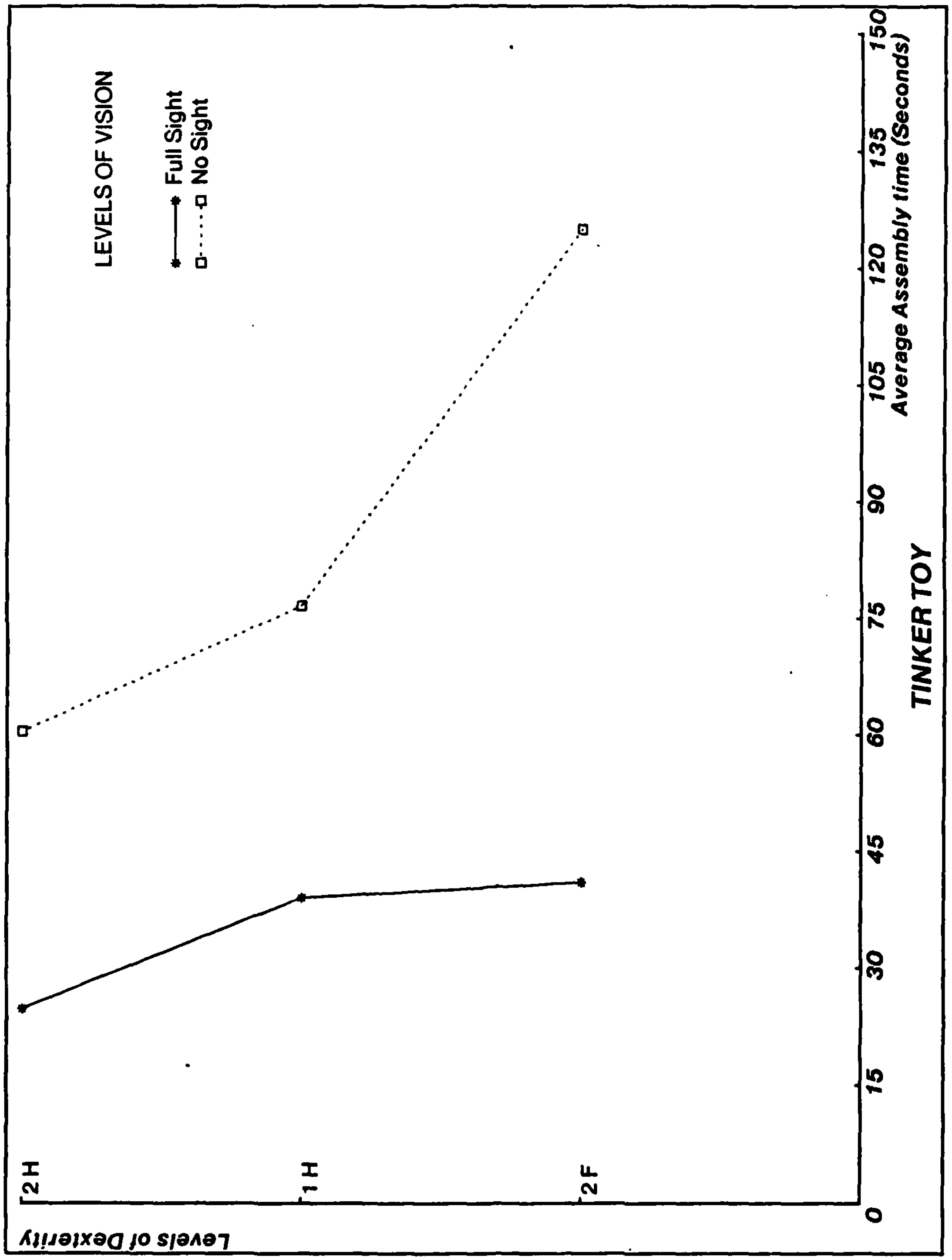

Table 1-15: Percent Change in Average Assembly Times:
Level of Vision Fixed at Full Sight or No Sight;
Level of Dexterity Varying

LEVEL OF VISION: FULL SIGHT

Change in Level of Dexterity From:	P.S.	N. & B.	F.L.	T.T.	C. & W.
2H to 1H	43	*	73	57	4
1H to 2F	21	*	2	5	23

LEVEL OF VISION: NO SIGHT

Change in Level of Dexterity From:	P.S.	N. & B.	F.L.	T.T.	C. & W.
2H to 1H	64	*	27	27	**
1H to 2F	47	*	61	63	**

*: Experiments not performed.
**: Experiments could not be completed accurately.

2H: Two hands
1H: One hand
2F: Two fingers (thumb and forefinger)

Note: all experiments performed with no gloves (bare hands).

Table 1-16: Percent Change in Assembly Times:
Level of Dexterity Fixed; Level of Vision Varying from Sight to No Sight

	Percent Change in Assembly Time:				
	P.S.	N. & B.	F.L.	T.T.	C. & W.
DEXTERITY LEVEL: TWO HANDS					
FS to NS	114	*	73	143	**
DEXTERITY LEVEL: ONE HAND					
FS to NS	145	*	27	96	**
DEXTERITY LEVEL: TWO FINGERS					
FS to NS	199	*	100	205	**

*: experiments not performed.

**: experiments could not be completed accurately.

FS: full sight

NS: no sight (blindfolded)

Note: all experiments performed with no gloves (bare hands).

2. The Effects on Varying Sensory Information on Manipulative Subtasks

2.1 Overview

From the discussions of the results of assembling the devices, it is evident that we need to focus on how changes in sensory information affect the more elemental subtasks. The Methods Time Measurement (MTM) system is used as the basis for categorizing manipulative subtasks.[21] The elemental MTM motions are

- reach
- grasp
- move
- position
- turn
- crank
- release

Most of the elemental motions are broken down further into different cases. For example, the elemental task "position" is divided into these finer subtasks:

- orient
- primary engage
- align
- secondary engage

For each subtask (each case distinguished within each elemental motion), we estimate how its completion time is affected by a change in the amount of sensory information available. We make one addition to the MTM task classification. Since positioning is such an important part of assembly, we further differentiate between the most common types of positioning operations. A breakdown of the different types of positioning considered is shown in Table 2-1. These positioning types are taken from a classification of unit assembly operations developed by Kondoleon at the Charles Stark Draper

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[21] See Antis, W., J.M. Honeycutt and E.N. Koch, The Basic Motions of MTM, Fifth Edition, The Maynard Foundation, Naples, Florida, 1979.

Lab.[22] These types of positioning are the five unit operations which Kondoleon found to occur most frequently in assembly. Then, within each of these types of positioning, we examine how the subtasks of orienting, primary engaging, aligning and secondary engaging are affected by changes in sensory information.

Differences in subtask completion times are examined under the following conditions:

1) Level of Vision: fixed at Full Sight (FS)
Level of Taction: varied from NG to LG, from NG to HG, from NG to WG

2) Level of Vision: fixed at No Sight (NS)
Level of Taction: varied from NG to LG, from NG to HG, from NG to WG

3) Level of Taction: fixed at NG
Level of Vision: varied from FS to NS

4) Level of Taction: fixed at LG
Level of Vision: varied from FS to NS

5) Level of Taction: fixed at HG
Level of Vision: varied from FS to NS

6) Level of Taction: fixed at WG
Level of Vision: varied from FS to NS

For each elemental motion examined, a table is presented in the next section showing the extent to which subtask completion times are affected by a change in taction for a given level of vision (conditions 1 and 2 above). Following that is a second table showing the extent to which subtask completion times are affected by a change in the level of vision for a given level of taction (conditions 3-6 above).

The measurements of percent changes in subtask completion times in these tables is not precise. They were made by replaying the video tapes of the experiments on a regular TV monitor and timing the start and stop of the subtask with a stop watch.[23] Because of the difficulty of timing subtasks in this fashion, we only distinguish between the following cases:

small decrease (SD)	0 to 20 % decrease in time

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[22] See Nevins, James L. and Daniel E. Whitney, "Computer-Controlled Assembly", Scientific American, Vol. 238, No. 2, February 1978, pages 62-75.

[23] More accurate measurements could be made by using a frame by frame analyzer. However, we did not have access to such an instrument.

Table 2-1: Types of Positioning Considered and Frequency of Occurrence by Device

Positioning Subtask	Device			
	Pencil sharpener	Flash-light	Tinker Toy	Wire and Chip
Simple peg in hole	2	2	-	4
Push and twist	-	1	-	-
Multiple peg in hole	-	-	-	2
Screw	1	1	-	-
Force fit	-	1	8	-

Numbers give the number of times a particular type of positioning operation occur within a given assembly experiment.

no change (NC)	no measurable change in time
small increase (SI)	0 to 20 % increase in time
medium increase (MI)	20 to 60 % increase in time
large increase (LI)	60 to 90 % increase in time
very large increase (VLI)	90 % or greater increase in time

When one type of sensory input is restricted, we are most interested in noting the extreme changes, both small and large, in subtask execution time. Large and very large percentage increases in execution time indicate that a subtask is highly sensitive to a particular type of change in information. When execution times do not change or only increase or decrease by a small amount, then the subtask is relatively insensitive to the particular type of change in information. By noting the subtasks with the larger and smaller percent increases in execution time, we are able to make a preliminary estimate of those subtasks which are most affected and least affected by particular types of changes in sensory information.

For the elemental motions "grasp" and "position", a representative task from the experiments was chosen as the prototype and used to measure the percent changes. For example, the time to insert the batteries into the body of the flashlight was used as the prototype for the subtask "simple peg-in-hole with loose tolerances". A list of all of the prototypes used is given with the tables that follow.

2.2 Effects of Varying Sensory Information on Elemental Manipulative Subtasks: Summary Tables

Reach

Table 2-2: Level of vision fixed; level of taction varying
Table 2-3: Level of taction fixed; level of vision varying

For both levels of vision (full sight and no sight), reaching is unaffected by the the level of taction. With full sight, reducing the amount of taction information has no noticeable effect on the four types of reaching subtasks. Without vision, reducing taction has either no effect on reaching time or results in only a slight time increase, depending on the shift in levels of taction. It is maintained, therefore, that taction is not important for reaching. This is not at all surprising. Reaching only includes moving to an object. The grasping is considered as a separate subtask.

For a given level of taction, reaching times are affected when vision is reduced from full sight to no

sight. The extent of the increase depends on the amount of taction and on the complexity of the reaching subtasks. With full taction (no gloves), a loss of sight results in only a small increase in time, except in the case when one has to reach to very small objects. For each type of reach listed in the table, as the level of taction decreases, the impact of loosing visual information increases.

Grasp

Table 2-4: Prototype tasks used to measure time changes for different types of grasping
Table 2-5: Level of vision fixed; level of taction varying
Table 2-6: Level of taction fixed; level of vision varying

There are several cases where grasping with a presumably "less" tactile information is offset by a mechanical property of the hand covering which simplifies the grasping. For example, with either level of vision, when the hand covering is shifted from no gloves to light gloves, there is a slight decrease in subtask time when grasping an isolated object which is not very small. As explained earlier, we believe this is due to the increase in friction resulting from the "non-slip" surface of the dish washing glove. When grasping small objects or objects lying close against a flat surface, subtask times increase more when bare hands are covered with heavy gloves than with wooden splints. While the heavy rubber gloves presumably transmit more tactile information than the wooden splints, the rigid wooden splints apparently simplify the task of grasping small or thin objects.

Even with these anomalies, it is apparent that the ability to grasp under all of the situations listed is dependent on the amount of tactile information. This is the case with full sight and with no sight. With full sight, the most sense dependent situations are when grasping without any tactile feedback (wooden gloves), except when using rigid grippers to acquire small or flat objects. When grasping small or thin objects with full sight, the most sense dependent situation is when using heavy (bulky) gloves. Without sight, the most sense dependent situations are the same as with sight.

When the level of taction is fixed and visual information is eliminated, not all of the subtask completion times for the different types of grasps are affected. As long as there is at least a crude level of taction (heavy gloves), grasping isolated objects which are not very small is not affected much by a loss of vision. This type of grasping is not sensitive to the the amount of visual information. Grasping small or flat objects is not very sensitive to a loss in sight if there is high level of tactile information available (light gloves or no gloves). However, with very low levels of taction, this grasping subtask is sensitive to a losing visual information. The same conditions appear to hold for grasping small objects jumbled up with one another as for grasping small or thin objects which are isolated.

Move

Table 2-7:	Level of vision fixed; level of taction varying
Table 2-8:	Level of taction fixed; level of vision varying

Given a level of visual information, moving an object to either an approximate or an exact location is sensitive to changes in the level of tactile information. If the change in taction is only slight, there is no effect on subtask time. As tactile information is more fully restricted, the effect on subtask completion time increases.

The impact of losing vision on moving times depends on the amount of tactile information available in the usual way. The less tactile information, the greater the impact of losing vision on subtask completion times. With high levels of taction, the move subtasks are not very sensitive to a loss of sight, especially if only moving to an approximate location. With very low levels of taction, moving to an exact location is very sensitive to a loss of vision.

Position

Table 2-9:	Prototype tasks used to measure time changes for different types of positioning
Table 2-10:	Level of vision fixed; level of taction varying
Table 2-11:	Level of taction fixed; level of vision varying

With loose tolerances, the simple peg-in-hole task is not sensitive to decreases in the amount of tactile information. This is the case with full sight and without sight. With close tolerances, this subtask is still not sensitive to decreases in tactile information as long as there is a high level of visual information. Without sight, the subtasks of alignment and secondary engagement become increasing sensitive to larger decreases in the amount of tactile information. With exact tolerances, the simple peg-in-hole more of the positioning subtasks become more strongly affected by a loss in tactile information. Alignment and secondary engage are the subtasks which seem to be the most affected by changes in the level of tactile information, especially when there is no visual information.

The Multiple peg-in-hole type of positioning shows a pattern that was also present in the data for grasping. Without sight, the impact of shifting from no gloves to heavy gloves is larger than the impact of shifting from no gloves to wooden gloves. This is probably another situation where it is easier to perform a task with rigid wooden grippers than with bulky rubber gloves, despite the fact that the gloves presumably transmit more tactile information. In general, the greater the decrease in the level of tactile information, the greater the impact on subtask completion times for the multiple peg-in-hole operation.

When trying to insert a screw into a screw hole with full vision, only the alignment subtasks seems to

be sensitive to taction, and then only when there is a very large decrease. Without sight, the primary and secondary alignment steps also become very sensitive to large decreases in the level of taction.

Force fitting one piece into another is not strongly affected by loses in taction as long as there is full vision. Without sight, the steps of primary engagement, alignment and secondary engagement become increasingly sensitive with increasing restrictings on the availability of tactile information.

With full sight and without sight, the push and twist subtask follows much the same pattern as the force fit task. Primary engagement, alignment and secondary engagement become increasingly sensitive with increasing restrictings on the availability of tactile information.

The simple peg-in hole task with loose tolerances is not very sensitive to loses in sight, especially if there is at least a very crude sense of taction. With close tolerances, a lose of sight causes a large increase in time if there is only a crude sense of taction. With exact tolerances, the primary engagement, alignment and secondary engagement are all very sensitive to losing sight, even when the level of taction is very high. Multiple peg-in-hole follows the same pattern as simple-peg-in-hole with exact tolerances as does force fitting.

When positioning a screw, the lose of sight results in a significant time increase when there is only crude levels of taction, but not when there is a high level of taction. Pushing and twisting follows a similar pattern as positioning a screw.

Turn and Crank

Table 2-12: Level of vision fixed; level of taction varying
Table 2-13: Level of taction fixed; level of vision varying

When shifting from no gloves to light gloves for turning, time often decreases. This also happened with grasping. The suggested reason for the decreased is related to the improved gripping surface provided by the surface of the lightweight dish washing glove. Aside from that, the impact on subtask completion time increases as the level of taction is reduced.

With sight, cranking is not very sensitive to a lose in tactile information. Without sight, however, cranking times are substantially increased when the level of taction is greatly or fully reduced.

When visual input is eliminated, turning times are not strongly affected if there is at least a crude level of taction. However, if there is practically no taction, the lose of sight results in a large time increase. Cranking seems to be more somewhat more sensitive to a lose of sight than turning.

Release

Table 2-14: Level of vision fixed; level of taction varying
Table 2-15: Level of taction fixed; level of vision varying

Releasing is not affected by decreases in either the levels of visual or tactile information. It is independent of the amount of sensory information processing.

Key to Tables

SD	small decrease	0 to 20 % decrease in time
NC	no change	no measurable change in time
SI	small increase	0 to 20 % increase in time
MI	medium increase	20 to 60 % increase in time
LI	large increase	60 to 90 % increase in time
VLI	very large increase	90 % or greater increase in time

TABLE II- 2: REACH: Level of Vision Fixed; Level of Taction Varying

MTM MOTIONS	SIGHT			NO SIGHT		
	NG/LG	NG/HG	NG/WG	NG/LG	NG/HG	NG/WG
A. Reach to object in fixed location, or to object in other hand or on which other hand rests						
B. Reach to single object in location which may vary slightly from cycle to cycle	NC	NC	NC	NC	SI	SI
C. Reach to objects jumbled with other objects in a group so that search and select occur	NC	NC	NC	NC	SI	SI
D. Reach to a very small object or where accurate grasp is required	NC	NC	NC	NC	SI	SI

TABLE II-3: REACH: Level of Taction Fixed; Level of Vision Varying

MTM MOTIONS	NG	LG	HG	WG
	S/NS	S/NS	S/NS	S/NS
A. Reach to object in fixed location, or to object in other hand or on which other hand rests				
B. Reach to single object in location which may vary slightly from cycle to cycle	SI	SI	MI	LI
C. Reach to objects jumbled with other objects in a group so that search and select occur	SI	MI	LI	VLI
D. Reach to a very small object or where accurate grasp is required	LI	LI	VLI	VLI

TABLE II-4: PROTOTYPE TASKS USED TO MEASURE TIME CHANGES FOR GRASPING

ELEMENTAL MOTION: GRASPING

Subtask	Prototype for Measurement of Time Changes
Picking up any size object by itself, easily grasped	batteries and sharpener of pencil sharpener
Picking up an object with a diameter larger than 1/2"	same as above
Picking up an object very small or lying close against a flat surface	lens of flashlight, flexible wires and flat chip
Picking up an object with a diameter less than 1/4"	same as above
Selecting objects jumbled with other objects so search and select occur	Early version of nut and bolt experiment

*) In an early version of the nut and bolt experiment, several nuts were jumbled with one another These experiments were recorded, but not used. In the later version of the experiemnt, a nut was placed on a part holder.

Table II-5: GRASP: Level of Vision Fixed; Level of Taction Varying

MTM Motions	SIGHT			NO SIGHT		
	NG/LG	NG/HG	NG/WG	NG/LG	NG/HG	NG/WG
1A Any size object by itself, easily grasped	NC/SD	SI	LI	NC/SD	SI	LI
1B Object very small or lying close against a flat surface	NC/SI	LI	(a) MI	NC/SI	VLI	LI
1C1 Diameter larger than 1/2"	NC/SD	SI	LI	NC/SD	SI	LI
1C3 Diameter less than 1/4"	NC/SI	LI	(a) MI	NC/SI	VLI	LI
4B 1/4" x 1/4" x 1/8" to 1" x 1" x 1" (Objects jumbled)			LI			VLI

(a) Wooden Splints actually make it easier to pick up a flat object

Table II-6: GRASP: Level of Taction Fixed; Level of Vision Varying

MTM Motions	NG S/NS	LG S/NS	HG S/NS	WG S/NS
1A Any size object by itself, easily grasped	NC	NC	SI	MI
1B Object very small or lying close against a flat surface	SI	SI	LI	LI
1C1 Diameter larger than 1/2"	NC	NC	SI	MI
1C3 Diameter less than 1/4"	SI	SI	LI	LI
4B 1/4" x 1/4" x 1/8" to 1" x 1" x 1" (Objects jumbled)	SI	SI	LI	LI

TABLE II- 7: MOVE: Level of Vision Fixed; Level of Taction Varying

MTM MOTIONS	SIGHT			NO SIGHT		
	NG/LG	NG/HG	NG/WG	NG/LG	NG/HG	NG/WG
A. Move object to other hand or against stop						
B. Move object to approximate or indefinite location	NC	(a) SI	(b) LI	NC	(a) LI	(b) VLI
C. Move object to exact location	NC	MI	LI	NC	LI	VLI

(a) With heavy gloves, there are problems placing an object

(b) *With wooden splints, tend to drop object when releasing* it at its destination. This causes positioning problems.

TABLE II-8: MOVE: Level of Taction Fixed; Level of Vision Varying

MTM MOTIONS	NG S/NS	LG S/NS	HG S/NS	WG S/NS
A. Move object to other hand or against stop				
B. Move object to approximate or indefinite location	SI	SI	MI	LI
C. Move object to exact location	MI	MI	LI	VLI

TABLE II-9: Prototype Tasks Used to Measure Time Changes for Positioning

ELEMENTAL MOTION: POSITIONING

Subtask	Prototype for Measurement of Time Changes
Simple peg-in-hole, loose tolerance	Insert batteries in flashlight tolerance: 0.15"
Simple peg-in-hole, close tolerance	Insert sharpener of Ps into base tolerance: 0.01"
Simple peg-in-hole, exact tolerance	Insert wire into circuit board
Multiple peg-in-hole	Insert chip into circuit board
Screw	Screw nut onto bolt
Force fit	Insert tinker-toy rod into holder
Push and twist	Put flashlight subassembly (lens hood, lens, bulb and reflecting hood) onto flashlight body

TABLE II-10: POSITION: Level of Vision Fixed; Level of Taction Varying

MTM MOTIONS	SIGHT			NO SIGHT		
	NG/LG	NG/HG	NG/WG	NG/LG	NG/HG	NG/WG
Simple Peg-in-Hole; Loose						
A. Orient	NC	NC	NC	NC	SI	SI
B. Primary Engage	NC	NC	NC	NC	SI	SI
C. Align	NC	NC	NC	NC	SI	SI
D. Secondary Engage	NC	NC	NC	NC	SI	SI
Simple Peg-in-Hole; Close						
A. Orient	NC	NC	NC	NC	SI	SI
B. Primary Engage	NC	NC	NC	NC	SI	MI
C. Align	NC	NC	NC	NC	MI	LI
D. Secondary Engage	NC	NC	NC	NC	MI	LI
Simple Peg-in-Hole; Exact						
A. Orient	NC	NC	NC	NC	SI	SI
B. Primary Engage	NC	NC	NC	NC	LI	LI
C. Align	NC	NC	LI	NC	VLI	VLI
D. Secondary Engage	NC	NC	NC	NC	VLI	VLI

TABLE II-10 Continued: POSITION: Level of Vision Fixed; Level of Taction Varying

MTM MOTIONS	SIGHT			NO SIGHT		
	NG/LG	NG/HG	NG/WG	NG/LG	NG/HG	NG/WG
Multiple Peg Hole						
A. Orient	NC	NC	NC	NC	LI	LI
B. Primary Engage	NC	NC	NC	NC	VLI	VLI
C. Align	NC	NC	NC	NC	VLI	VLI
D. Secondary Engage	NC	NC	NC	NC	VLI	VLI
Screw						
A. Orient	NC	NC	NC	NC	SI	SI
B. Primary Engage	NC	NC	NC	NC	LI	LI
C. Align	NC	NC	LI	NC	VLI	VLI
D. Secondary Engage	NC	NC	NC	NC	VLI	VLI
Force Fit						
A. Orient	NC	NC	NC	NC	NC	NC
B. Primary Engage	NC	SI	MI	NC	LI	VLI
C. Align	NC	SI	MI	NC	LI	VLI
D. Secondary Engage	NC	SI	MI	NC	LI	VLI
Push and Twist						
A. Orient	NC	NC	NC	NC	SI	SI
B. Primary Engage	NC	SI	SI	NC	LI	VLI
C. Align	NC	SI	MI	NC	LI	VLI
D. Secondary Engage	NC	SI	MI	NC	LI	VLI

TABLE II-11: POSITION: Level of Taction Fixed; Level of Vision Varying

MTM MOTIONS	NG S/NS	LG S/NS	HG S/NS	WG S/NS
Simple Peg-in-Hole; Loose				
A. Orient	NC	NC	NC	NC
B. Primary Engage	SI	SI	SI	MI
C. Align	SI	SI	SI	MI
D. Secondary Engage	SI	SI	SI	MI
Simple Peg-in-Hole; Close				
A. Orient	NC	NC	SI	MI
B. Primary Engage	MI	MI	LI	VLI
C. Align	MI	MI	LI	VLI
D. Secondary Engage	MI	MI	LI	VLI
Simple Peg-in-Hole; Exact				
A. Orient	NC	NC	MI	LI
B. Primary Engage	LI	LI	VLI	VLI
C. Align	LI	LI	VLI	VLI
D. Secondary Engage	LI	LI	VLI	VLI

TABLE II-11 Continued: POSITION: Level of Taction Fixed; Level of Vision Varying

MTM MOTIONS	NG S/NS	LG S/NS	HG S/NS	WG S/NS
Multiple Peg Hole				
A. Orient	NC	NC	MI	LI
B. Primary Engage	LI	LI	VLI	VLI
C. Align	LI	LI	VLI	VLI
D. Secondary Engage	LI	LI	VLI	VLI
Screw				
A. Orient	NC	NC	SI	MI
B. Primary Engage	MI	MI	LI	VLI
C. Align	MI	MI	LI	VLI
D. Secondary Engage	MI	MI	LI	VLI
Force Fit				
A. Orient	NC	NC	MI	LI
B. Primary Engage	LI	LI	VLI	VLI
C. Align	LI	LI	VLI	VLI
D. Secondary Engage	LI	LI	VLI	VLI
Push and Twist				
A. Orient	NC	NC	MI	LI
B. Primary Engage	MI	MI	VLI	VLI
C. Align	MI	MI	VLI	VLI
D. Secondary Engage	MI	MI	VLI	VLI

TABLE II-12: TURNING & CRANKING: Level of Vision Fixed; Level of Taction Varying

TURN

MTM MOTIONS	SIGHT			NO SIGHT		
	NG/LG	NG/HG	NG/WG	NG/LG	NG/HG	NG/WG
Small-0-2 lbs-180 degrees	NC/SD	SI	LI	NC/SD	LI	VLI

CRANK

MTM MOTIONS	SIGHT			NO SIGHT		
	NG/LG	NG/HG	NG/WG	NG/LG	NG/HG	NG/WG
Diameter - 2 inches	NC	SI	MI	NC	LI	VLI

TABLE II-13: TURNING & CRANKING: Level of Taction Fixed; Level of Vision Varying

TURN

MTM MOTIONS	NG S/NS	LG S/NS	HG S/NS	WG S/NS
Small-0-2 lbs-180 degrees	NC	NC	MI	VLI

CRANK

MTM MOTIONS	NG S/NS	LG S/NS	HG S/NS	WG S/NS
Diameter - 2 inches	SI	SI	VLI	VLI

TABLE II-14: RELEASING: Level of Vision Fixed; Level of Taction Varying

MTM MOTIONS	SIGHT			NO SIGHT		
	NG/LG	NG/HG	NG/WG	NG/LG	NG/HG	NG/WG
(1) Normal release, performed by opening fingers as independent motion	NC	NC	NC	NC	SI	SI

TABLE II-15: RELEASING: Level of Taction Fixed; Level of Vision Varying

MTM MOTIONS	NG S/NS	LG S/NS	HG S/NS	WG S/NS
(1) Normal release performed by opening fingers as independent motion	NC	NC	SI	SI

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